U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-286 905

Guidance Manual for Minimizing Pollution from Waste Disposal Sites

A. W. Martin Associates, Inc, King of Prussia, PA

Prepared for

Municipal Environmental Research Lab, Cincinnati, OH

Aug 78

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-78-142
August 1978

Research and Development

PB 286905

EPA

Guidance Manual for Minimizing Pollution from Waste Disposal Sites

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-78-142	2.
3. RECIPIENT'S ACCESSION NO. PB286905	
4. TITLE AND SUBTITLE Guidance Manual for Minimizing Pollution from Waste Disposal Sites	5. REPORT DATE August 1978 (Issuing Date)
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Andrew L. Tolman, Antonio P. Ballestero, Jr., William W. Beck, Jr., and Grover H. Emrich	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS A.W. Martin Associates, Inc. 900 W. Valley Forge Road King of Prussia, Pennsylvania 19406	10. PROGRAM ELEMENT NO. 1DC618 (SOS 3, Task 03)
	11. CONTRACT/GRANT NO. 68-03-2519
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED Final
	14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES
Project Officer - Donald E. Sanning - 513/684-7871

16. ABSTRACT
This manual provides guidance in the selection of available engineering technology to reduce or eliminate leachate generation at existing dumps and landfills. The manual emphasizes remedial measures for use during or after closure of landfills and dumps which do not meet current environmental standards. Most of the techniques discussed in the report deal with the reduction or elimination of infiltration into landfills in one of five categories, active groundwater or plume management, chemical immobilization of wastes, and excavation and reburial. The technology presented is widely used in construction but has not necessarily as yet been applied to landfill closure. The report was submitted in fulfillment of Contract No. 68-03-2519 by A.W. Martin Associates, Inc. of King of Prussia, Pennsylvania. The work was completed May 17, 1978.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Attenuation, Barriers, Linings, Deactivation, Stabilization, Bentonite, Optimization, Waste Disposal, Sites, Engineering Costs, Design Criteria	Groundwater Pollution Leachate Minimization	13B 68C 89B

18. DISTRIBUTION STATEMENT PUBLIC DISTRIBUTION	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 95
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE PC A05 MF A01

EPA Form 2220-1 (Rev. 4-77)

* U.S. GOVERNMENT PRINTING OFFICE: 1978— 757-140/1425

EPA-600/2-78-142
August 1978

GUIDANCE MANUAL FOR MINIMIZING POLLUTION FROM WASTE DISPOSAL SITES

by

Andrews L. Tolman
Antonio P. Ballestero, Jr.
William W. Beck, Jr.
Grover H. Emrich
A. W. Martin Associates, Inc.
King of Prussia, Pennsylvania 19406

Contract No. 68-03-2519

Project Officer

Donald E. Sanning
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This manual is intended as a general guide for municipal officials faced with closing or neutralizing solid waste disposal sites. It presents an overview of standard engineering practices that can be applied to minimize pollution from inactive waste disposal sites.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

PREFACE

Most of the municipal refuse in the United States is disposed of in approximately 15,000 sites, two-thirds of which are open dumps. The Solid Waste Disposal Act as amended by the Resource Conservation and Recovery Act (RCRA) of 1976 requires the phasing out of open dumps within the next 5 years. With the implementation of RCRA and more stringent State solid waste disposal practices it is anticipated that the majority of the approximately 10,000 open dumps will be closed within the next 5 years and increased volumes of solid waste will be disposed of in existing permitted sanitary landfills.

Closing open dumps and upgrading existing landfills both involve minimizing or eliminating the potential for resource contamination, or "neutralizing" the waste disposal site. Neutralization measures are used to reduce the amount or concentration of the contaminants produced and/or to prevent or redirect their movement from the disposal site.

This manual has been prepared to introduce municipal officials to the subject of neutralizing existing and abandoned waste disposal sites. Well known engineering practices which have not been extensively applied to the solid waste field can be used for site neutralization. Various methods for preventing environmental degradation and estimates of their costs are presented herein.

This guide is not intended as a design manual. The plans and specifications for application of any method presented must be designed by competent professionals on a site-specific basis. Actual cost estimates for use of these methods will also have to be developed on the basis of current labor and construction costs in the specific area being considered. The procedures and estimates included in this manual are generalized. Therefore, for neutralization of some waste disposal sites the methods may be suitable, while for other sites, because of their size or specific characteristics, these methods may be impractical.

This manual represents one phase of a multiphase project being conducted under U.S. EPA Contract No. 68-03-2519 by A. W. Martin Associates, Inc. Other phases involve the selection of an abandoned waste disposal site for study, the design and implementation of remedial neutralization procedures, and the implementation of a monitoring program to determine the effectiveness of the procedures.

ABSTRACT

The purpose of this manual is to provide guidance for municipal officials and engineers in the selection of available engineering technology to reduce or eliminate leachate generation at existing dumps and landfills. The manual emphasizes remedial measures for use during or after closure of landfills and dumps which do not meet current environmental standards. All of these measures must be designed and engineered by competent professionals for each specific site. Some of these measures are passive, that is, they require little or no maintenance once emplaced. Others are active and require a continuing input of manpower or electricity. Since the emphasis of this manual is on techniques of reducing leachate generation or controlling its movement, leachate treatment processes per se are not detailed.

Most of the techniques discussed herein deal with the reduction or elimination of infiltration into landfills in one of five categories: surface water control, passive groundwater management, active groundwater or plume management, chemical immobilization of wastes, and excavation and reburial. The technology presented is widely used in construction but has not necessarily as yet been applied to landfill closure.

Surface water control measures include contour grading, surface sealing, and revegetating the landfill. These methods reduce infiltration of precipitation through the landfill surface, involve standard engineering procedures, and provide a means of finishing the site.

Passive groundwater control techniques are used to minimize infiltration of groundwater into the fill. They involve more technically advanced engineering procedures designed to provide an underground barrier between the groundwater and the landfill. They are generally more costly and are useful for isolating a landfill when applied in conjunction with surface sealing methods.

Plume management procedures involve actively altering the course of leachate movement by either adding or removing water from around the landfill. These methods can effect greater changes in water table elevations than can passive barriers but require continued maintenance and energy supplies and are therefore more costly.

Chemical immobilization techniques include (1) the application of chemically stabilized materials to the landfill as a surface seal and (2) the injection of chemicals into the landfill to destroy a potential contaminant. Only the first of these is recommended as feasible for in situ landfill neutralization. Chemical injection involves fairly sophisticated and expensive technology.

Excavation and reburial of a landfill entails removing the fill material from its present location and reburying it in an engineered and environmentally sound landfill. The procedure is effective but costly and technically difficult. It would be recommended only for a severe pollution problem.

This report was submitted in partial fulfillment of Contract No. 68-03-2519 by A. W. Martin Associates, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from February 1977 to September 1977, and work was completed as of March 1978.

CONTENTS

Foreword iii
Preface iv
Abstract v
Figures viii
Tables ix

1. Introduction. 1
2. Surface Water Control 5
   Contour grading and surface water diversion. . . 5
   Surface sealing. 9
   Revegetation 15
3. Groundwater Control 20
   Bentonite slurry-trench cutoff wall. 21
   Grout curtain. 25
   Sheet piling cutoff wall 32
   Bottom sealing 35
4. Plume Management. 39
   Extraction 39
   Injection. 47
   Leachate handling. 48
5. Chemical Immobilization 52
   Chemical fixation. 52
   Chemical injection 56
6. Excavation and Reburial 62
7. Summary 65
   Surface water control. 65
   Groundwater control. 67
   Plume management 68
   Chemical immobilization. 70
   Excavation and reburial. 70

References 72
Appendix

Unit Costs Used as Basis for Cost Estimates 78

FIGURES

Number		Page
1	Generalized cross section of hypothetical landfill case	2
2	Cross section showing water flow into and away from hypothetical landfill	3
3	Cross section of landfill showing contour grading and surface water diversion.	6
4	Cross section of capped landfill	10
5	Plan view of semicircular slurry-trench cutoff wall around upgradient end of landfill.	21
6	Cross section of landfill before and after slurry-trench cutoff wall installation.	22
7	Cross section of grout curtain at landfill	26
8	Soil limits of grout injectability	27
9	Typical two-row grid pattern for grout curtain	29
10	Semicircular grout curtain around upgradient end of landfill.	30
11	Cross section of sheet piling cutoff wall at landfill	34
12	Cross section of grouted bottom seal beneath landfill	36
13	Cross section of drain downgradient from the landfill	41
14	Plan view of well points or extraction wells used to lower the water table upgradient from the landfill	42
15	Cross section of extraction well at landfill	44
16	Cross section of landfill sealed with stabilized waste material	54
17	Pollution plume created by cyanide salts located in the middle of hypothetical landfill	58
18	Cross section of landfill treated by chemical injection.	60

TABLES

Number		Page
1	Relative Costs of Grout.	31
2	Present Worth of Leachate Recycling Systems.	51
3	Requirements for Chemical Treatment of Cyanide Pollution at Hypothetical Landfill	59
4	Summary of Estimated Costs and Characteristics of Remedial Methods.	66

SECTION 1

INTRODUCTION

To ensure comparable cost estimates for the neutralization methods presented in this manual, a hypothetical landfill site was developed (see Figure 1). The standard unit costs used in estimating are included in the Appendix. The assumed hypothetical site is a 4-hectare (10-acre) landfill located in the northeastern United States in a depression situated on a slope between an upland groundwater recharge area and a groundwater discharge area with a stream. The landfill is underlain by 30 m (100 ft) of unconsolidated, fairly permeable materials of either glacial, coastal, or saprolitic origin, underlain by an indeterminate bedrock. The water table is 6 m (20 ft) below the ground surface and the lower 3 to 5 m (10 to 15 ft) of the landfill is in the groundwater.

The landfill originated as a pushover burning dump. The waste is 12 to 15 m (40 to 50 ft) deep and extends 3 to 5 m (10 to 15 ft) above the ground surface. The bottom 3 to 5 m (10 to 15 ft) was dumped rather than landfilled and is located below the water table. The remaining waste was landfilled and covered with very sandy material. Mainly municipal refuse has been accepted at the site. However, during the time it was operated as a dump, no records of the materials deposited were kept, and it is possible that several nearby industries may have dumped industrial and/or hazardous wastes into the landfill.

A source of pollution from a municipal landfill is leachate, which is an odorous, colored substance generated when water comes into contact with municipal refuse. Leachate is generally of high ionic strength and variable pH and may contain metallic ions or organic compounds in toxic concentrations. Although some leachate is generated during the initial compaction, settlement, and stabilization of the refuse, the majority is produced by water moving through the landfill. Water can enter a landfill through the top or upgradient side, and leave as leachate through the bottom or the toe (see Figure 2). As it moves through the fill the water leaches soluble ions and organic compounds from the waste and creates leachate. The leachate then percolates down through the fill and either seeps out the toe of the landfill and contaminates surface waters, or enters the groundwater which in turn may carry it to surface waters.

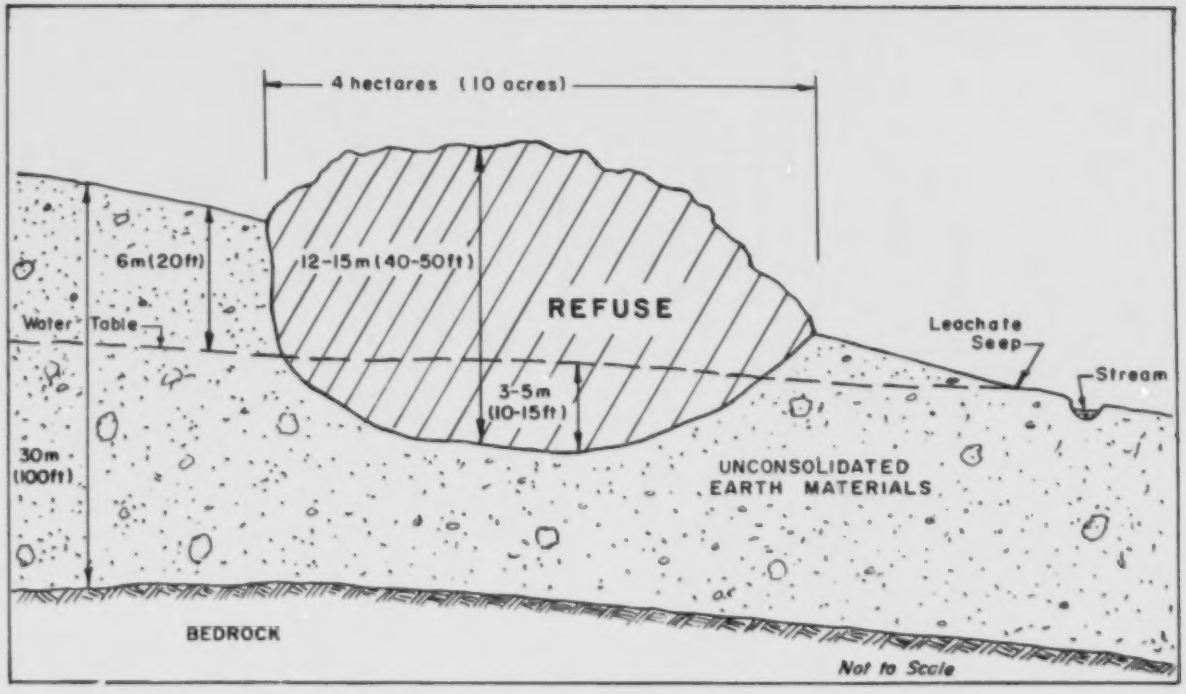
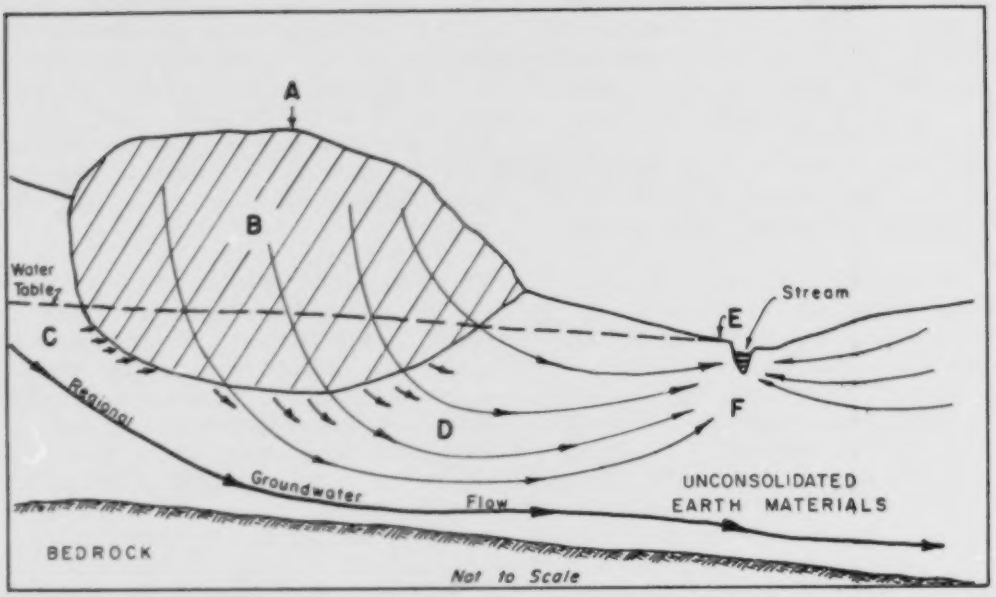


Figure 1. Generalized cross section of hypothetical landfill case.



KEY

A - Infiltration through uncovered refuse or cover material
B - Refuse containing leachable ions and organic substances that produce contamination when exposed to water
C - Groundwater inflow through upgradient end of landfill
D - Vertical or horizontal percolation from fill to groundwater, which may contaminate surface water
E - Leachate seepage
F - Local groundwater flow

Figure 2. Cross section showing water flow into and away from hypothetical landfill.

As shown on Figure 2, there are two main sources of water entering the hypothetical landfill: (1) precipitation falling on or running onto the landfill and infiltrating into the disturbed surface, and (2) groundwater flowing from the upgradient side through the lower portion of the landfill. The leachate produced initially enters the groundwater and discharges at several sidehill seeps below the toe of the fill which are highly stained and odorous. Much of the leachate travels in the groundwater to the stream and adjacent wetlands where it discharges and has a significant detrimental effect. There is a possibility that some of the leachate may be underflowing the stream (as shown on Figure 2) and moving into a regional groundwater system, in which case it could be affecting a number of water supply wells and a stream that feeds a local reservoir.

In order to stop a landfill from polluting ground and surface waters, it is necessary to (1) control leachate generation by changing the flow of water through the waste, (2) contain and remove the leachate produced, or (3) stabilize the waste material to prevent leaching of deleterious materials. This manual evaluates various methods of controlling leachate generation or retarding its movement. Most of the methods presented are passive methods of leachate control such as surface and subsurface infiltration barriers, which require little or no maintenance compared to active methods such as extraction or injection of water. All of the procedures included are designed to make the landfill site a less favorable environment for leachate production. These methods will result in a reduction of leachate volume; whether or not they decrease the contaminant loading will depend on the age and condition of the waste.

The manual is organized in five categories: surface water control, groundwater control, plume management, chemical immobilization, and excavation and reburial. These categories are presented from least to most technically complicated and costly. Since potentially there is more than one cause of leachate at a landfill (e.g., surface water, groundwater, waste pollutant) it may be necessary to combine methods from several of these categories to effectively control leachate generation.

SECTION 2

SURFACE WATER CONTROL

The most accessible part of a waste disposal site is its upper surface. In many cases, disposal sites are not designed to minimize the quantity of water infiltrating through the surface. An extreme example of this is a landfill in a sand and gravel pit which is not elevated to grade, is covered only with local material, and has not been revegetated. The contour and permeability of the cover in this case insure that nearly all precipitation falling on the fill is routed to the refuse; and this water generates large quantities of leachate.

This section presents three methods of reducing infiltration. The first is changing the contour and runoff characteristics of the landfill to reroute precipitation. The second is providing a barrier to infiltration by reducing the permeability of the land surface. The third is revegetating the site to stabilize the landfill cover material and increase seasonal evapotranspiration and interception to control infiltration. These three methods used together can be very effective in reducing the amount of water that enters the landfill surface, and can thereby reduce leachate generation considerably.

CONTOUR GRADING AND SURFACE WATER DIVERSION

Description

Contour grading of a landfill is a means of controlling and/or diminishing surface infiltration by reshaping the land and creating hills and valleys to promote and channel surface runoff (see Figure 3). Grading and compacting the landfill to a profile of a maximum of 12 percent and a minimum of 6 percent with side slopes no steeper than 18 percent will allow surface water to drain from the site and will minimize infiltration. Most soils will remain stable at these grades. Revegetated landfill surfaces that are too flat tend to retain water and increase infiltration. Ideally, to minimize overland routing areas subject to infiltration, the center of the landfill should be the highest elevation, with slopes of 18 percent maximum toward the landfill perimeter. Exact slopes to be used must be designed by a competent professional on the basis of soil type and slope stability at the site.

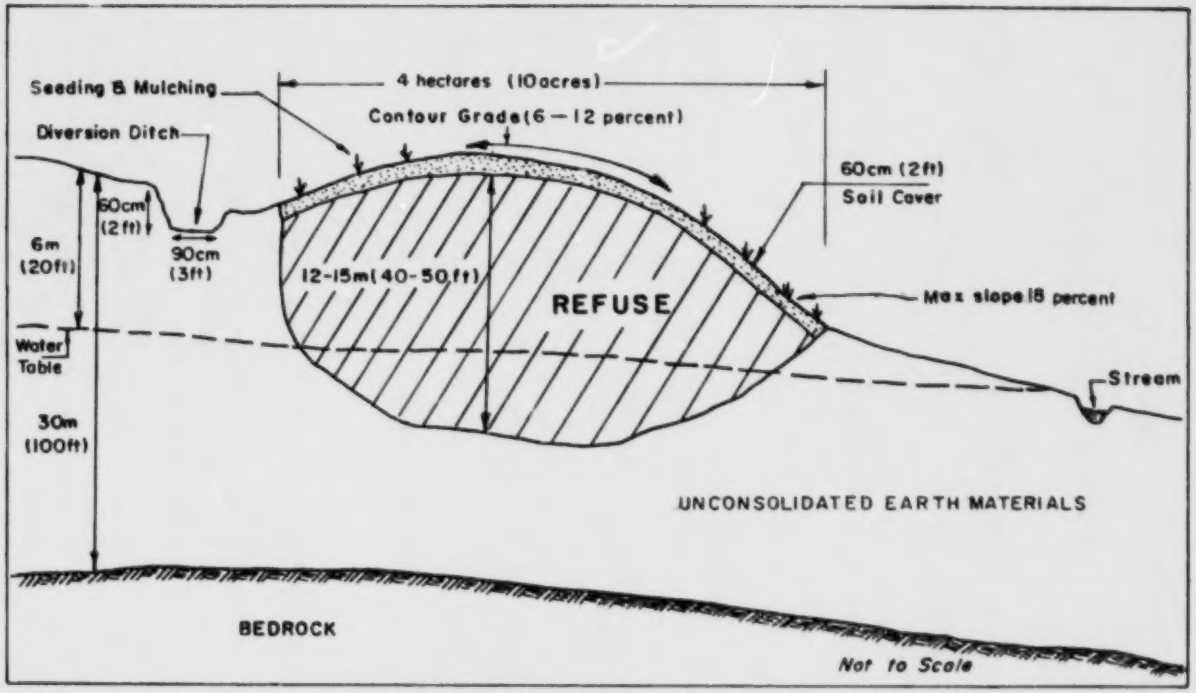


Figure 3. Cross section of landfill showing contour grading and surface water diversion.

Surface water diversion involves creating earth berms and excavating diversion ditches along the upslope side of the landfill, directed toward natural drainageways downslope from the landfill. Diversion ditches are designed to accommodate the characteristics of the contributing watershed such as area, annual rainfall, land use, soil type, topography, etc. Most commonly they are designed for 10-year storm intensity.

Erosion control is an important part of surface water diversion. Vegetation planted near and on the sides of diversion ditches will stabilize the soil. However, vegetation takes between 1 and 2 years to become firmly established. During that period, mulch and haybales can be used to stabilize these areas. Mulch can be pegged in place on steeper slopes.

The soils used for the final cover require careful evaluation (see Revegetation section). Such criteria as permeability, erodibility, fertility, and suitability for the ultimate use of the completed site must be investigated and documented. County Soil Conservation Service agencies can be contacted for information regarding available cover material and possible sources.

Clayey and silty loams are well suited for final cover. They are fertile enough to sustain acclimated native vegetation and are resistant to wind and surface water erosion. Coarse-grained soils are porous and highly permeable and are therefore not well suited for final cover. Soils composed predominantly of clays tend to shrink and crack when dry. Highly organic soils such as peat are difficult to compact and are usually associated with a high water content; when dry, they are extremely combustible and could be a fire hazard.

The distance between cover material borrow areas and the landfill can be an important cost consideration in final covering operations. If the distance is great, transportation costs will be high. The condition of haul roads and bridges must be considered in terms of the earth loads to be transported.

Decomposing municipal refuse in an anaerobic environment can generate significant quantities of methane and carbon dioxide. These gases can kill vegetation on or near the landfill and create a potential explosion hazard. Gas generation potential must be carefully evaluated based on the age, volume, composition, and moisture content of the waste. If this potential is high, provisions should be made for gas venting when the site is contoured and covered. Methods of gas venting are discussed in the Surface Sealing section of this manual.

Costs

The cost estimates presented here are based on contour grading the 4-hectare (10-acre) hypothetical landfill (shown on

Figure 1) to a maximum of 12 percent and a minimum of 6 percent slopes with side slopes of not more than 18 percent. This will involve moving and grading approximately 7,650 m^3 (10,000 yd^3) of municipal refuse, using 8,300 m^3 (10,750 yd^3) of fill material to complete the grading. The landfill surface will be covered with a minimum thickness of 0.6 m (2 ft) of soil cover. It is assumed that the cover and fill material will be transported from a borrow pit 8 km (5 miles) away. A contingency factor of $2,500 per hectare ($1,000 per acre) is incorporated into the total costs. Given these conditions, the total cost of grading and covering the landfill will range between $126,000 and $242,000.

A diversion ditch will be constructed around the upgradient end of the landfill. It will be 400 m (1,325 ft) long and extend halfway down each side of the landfill. Assuming the ditch is 0.6 m (2 ft) deep and 1 m (3 ft) wide, its total cost will range between $15,000 and $24,000.

Unit cost items 2, 4, and 7, were used in the calculations (see Appendix). Because contour-graded surfaces must be stabilized with vegetation, the costs of vegetating will also have to be considered. These costs are presented separately in the Revegetation section.

Evaluation

Advantages--

1. Construction operation is simple; common construction equipment is required; and basic engineering principles are involved.

2. Borrow pits are usually not difficult to find except in highly developed areas. Earth material can also be blended and mixed from several sources.

3. After grading, the landfill can be seeded and mulched to create large open spaces for recreation.

4. The method can be economical.

5. Covering, regrading, and revegetation of an uncovered, poorly graded landfill can increase runoff and evapotranspiration and virtually eliminate infiltration during the growing season. Net annual infiltration can be reduced more than 50 percent in ideal conditions. (The infiltration reduction for a particular site can be estimated using the water balance method.)

Disadvantages--

1. Differential settlement within the contoured landfill will necessitate periodic regrading to eliminate depressions.

2. Large quantities of cover material may be required to establish a slope to induce sheet flow of surface waters.

3. Suitable borrow pits may be located at a distance from the landfill, in which case transportation costs would be high.

Recommendations

Grading and surface water diversion measures are effective and economical standard procedures used in completing landfills. They promote surface runoff of precipitation, minimize (but not eliminate) vertical migration of rainfall, cover the landfill, and produce large, gently undulating land areas that can be revegetated and used for various forms of recreation.

References

For further discussion, see references 1 through 12.

SURFACE SEALING

Description

Surface sealing or capping is a method of landfill closure that involves the construction of an umbrella cap or seal on the landfill to prevent water infiltration and minimize leachate generation (see Figure 4). Caps and seals can be constructed of clays, fly ash, soils, soil-cement, lime-stabilized soil, membrane liners, bituminous concrete, and asphalt/tar materials using common earthmoving construction equipment and procedures. Stabilized waste materials can also be used for sealing as described in the Chemical Fixation section.

Prior to construction of any seal, the landfill surface must be contoured and compacted to provide a firm subgrade. Side slopes no steeper than 18 percent and top slopes of 12 percent maximum and 6 percent minimum are recommended. The existing cover material should be compacted to a Proctor density of 70 to 90 percent of maximum. Less compaction or steeper slopes could cause seal failure.

If the installation of a native clay seal is to be considered, field surveys will be required to determine the location, availability, and quantity of native clays in the area of the landfill. Compaction tests and permeability tests are useful in making these determinations. Where native clays are not available or available materials are low in clay content, the seal horizon can be fortified with bentonite clays. Bentonite can be added at the rate of 2 to 8 kg/m^2 (4 to 15 lb/yd^2), depending on the characteristics of the clay, and mixed or disced into the top 5 to 10 cm (2 to 4 in.) of the seal material.

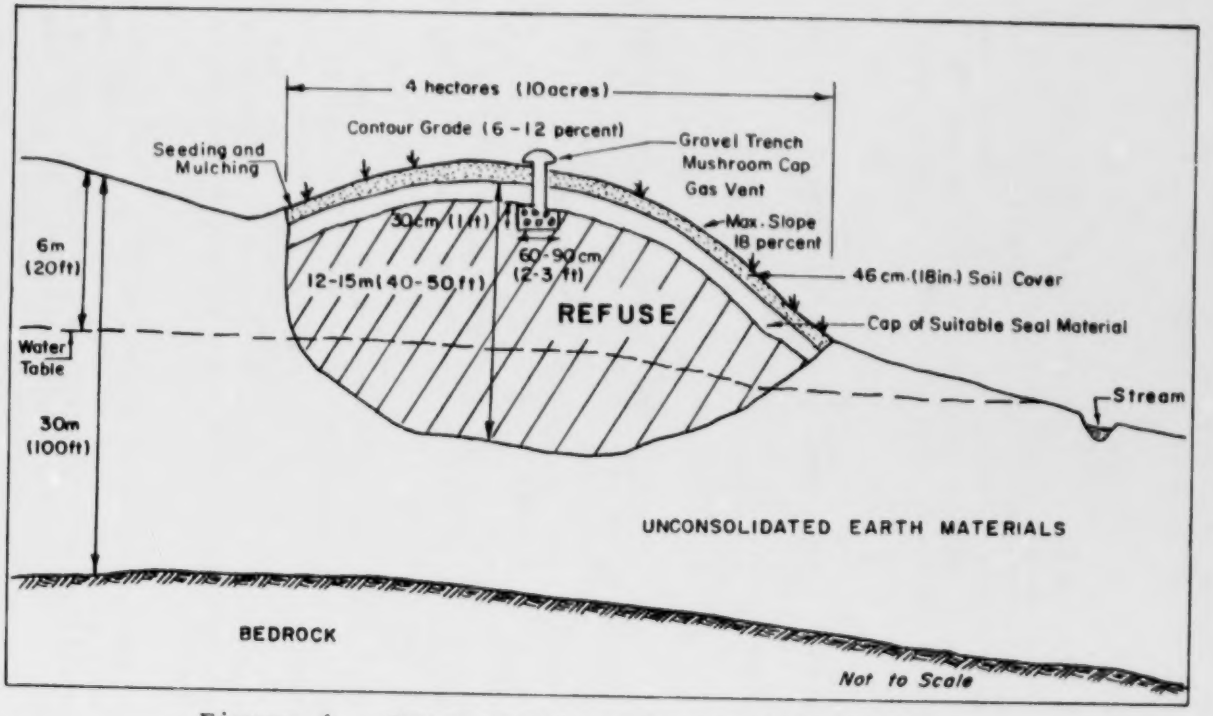


Figure 4. Cross section of capped landfill.

A bituminous concrete seal can be constructed on the prepared subgrade of the landfill using either a plant-mixed or job-site-mixed material. The plant-mixed material can be placed by asphalt macadam spreader machines and rolled with a 4.5- to 7.3-tonne (5- to 8-ton) steel-wheel roller. The site-mixed material can be placed by spreading the aggregate over the entire area, spraying the bitumen cement over the aggregate, and then placing a fine aggregate over the bitumen and rolling.

Fly ash is generally available in quantity from fossil-fuel energy generating systems. Because disposal of this material is a problem in many parts of the country, it can sometimes be obtained free of charge within a reasonable hauling distance of the generating system. However, in some states, fly ash may be considered a hazardous waste, and special permitting for its use would be required. Before this material is used for landfill surface sealing, chemical analyses will be necessary to ensure that it does not contain unsafe levels of hazardous elements.

In preparing the seal, fly ash can be deposited on the shaped landfill subgrade and spread by grader and bulldozer. Wobbly-wheeled (rubber-tired) rollers weighing from 4.5 to 7.3 tonnes (5 to 8 tons) are recommended for compacting the material. Water can be applied to the surface during compaction to minimize dust and aid in compaction.

Soil cement and lime-stabilized soils can be used to produce a sealed landfill surface. These methods involve mixing either cement or lime with soil and water to provide a relatively impermeable seal. A wide variety of soils are adaptable to these methods; however, sandy and gravelly soils have more favorable physical characteristics for use with soil cement, and clayey soils are more adaptable to lime stabilization. Laboratory analysis of soils is necessary to determine the most appropriate method as well as the amount of cement or lime required per unit area of landfill surface. Prior to application of either material, the entire surface of the landfill must be graded to the final desired contour. Cement or lime can then be added to the soil with mechanical spreaders and mixed into the soil. Commercial mixers/spreaders can also be used to add and mix the lime or cement as the soil is pulverized, which produces a uniform distribution of soil and cement or lime over the entire surface of the landfill. Once the soil and lime or cement have been completely mixed, water is added by sprinkler trucks at a rate determined by laboratory testing. The wetted surface is then rolled for proper compaction and allowed to cure. The resulting seal is impermeable and has greater structural integrity than the original soil.

Membrane liner material such as PVC, hypalon, polyethylene, etc., can also be used as an effective seal for the top surface of landfills. As with other methods of sealing, a properly

prepared subbase is essential. In this case, the subbase must be free of foreign materials that might puncture the membrane (e.g., sticks, metal, rocks). Abrupt changes in grade should be eliminated and the subbase should roughly conform to the final desired slope configuration. The membrane is placed over the completed subbase and the seams between the membrane sections are joined with heat or adhesive depending on the type of material. Each manufacturer of membrane liners has a recommended method of installation and standards for safe and stable cover material.

A soil cover is generally recommended but not always necessary over surface seals. Clay and fly ash are native materials that do not deteriorate with age. Some asphalt and membrane materials can be damaged by the sun when exposed, and therefore must be protected by a soil cover. Other membranes and asphalt compounds can be left exposed; however, for aesthetic purposes and/or to prevent vandalism of the seal, a soil cover may be desirable. At least 46 cm (18 in.) of final earth cover, preferably a silty or sandy loam, are recommended to support vegetative growth and protect the seal. The earth cover material can be transported by truck to the site, spread by grader or bulldozer, and rolled with a 2.7- to 4.5-tonne (3- to 5-ton) roller.

The sealed and covered landfill must be revegetated to stabilize the cover material and minimize infiltration (see Revegetation section). Annual and perennial grasses with roots not in excess of 38 to 46 cm (15 to 18 in.) are recommended. Periodic mowing may be necessary to control scrub growth, for aesthetic purposes as well as to prevent root penetration of the seal.

If the cover material used is of low permeability, an underdrain system may be required to ensure lateral drainage above the seal. An underdrain system can be constructed by laying 30 cm (12 in.) of 2-cm (0.75-in.) diameter clean stone in a regular network over the seal. Discharge from the drain is directed away from the landfill. The drainage field helps to minimize the amount of water retained in the final cover and direct water away from the surface seal. It provides further protection against water infiltrating through the seal into the landfill.

An important consideration in landfill surface sealing is gas venting. Some kind of opening such as a gravel trench with mushroom cap vent (shown on Figure 4) or gas venting wells must be provided to allow escape for the gases formed by decomposing refuse. The gas can be collected in trenches or wells and, if sufficient quantities are available, it can be used or sold.

As the landfill ages, the seal and earth cover will be subject to subsidence and settlement. Maintenance may be required to fill in depressions to avoid ponding of rain water.

Severe depressions can be corrected by filling in with earth and revegetating the fill material. If subsidence is severe and localized, however, the seal will have to be uncovered and examined for integrity. No other maintenance is anticipated.

Costs

The costs of constructing surface seals given in this section include the following:

excavation of 26,700 m^3 (34,950 yd^3) of common borrow material [8,200 m^3 (10,750 yd^3) for contouring to bring the surface to desired configuration, and 18,500 m^3 (24,200 yd^3) for the soil cover.]

excavation of 7,700 m^3 (10,000 yd^3) of the waste during grading operations.

earthmoving operations, grading and compacting materials, equipment and procedures for constructing each seal, including a contingency factor of $2,500 per hectare ($1,000 per acre).

The costs of the surface seals, complete in place for the 4-hectare (10-acre) landfill, including a 46-cm (18-in.) soil cover, are estimated as follows:

a. A 15-cm (6-in.) clay cap - $140,100 to $256,200.

b. A 46-cm (18-in.) clay cap - $180,400 to $328,700.

c. A 4-cm (1.5in.) bituminous concrete cap - $192,500 to $340,800.

d. A 13-cm (5in.) bituminous concrete cap - $289,300 to $437,600.

e. A 30-cm (12-in.) fly-ash cap - $136,100 to $247,300.

f. A 60-cm (24-in.) fly-ash cap - $179,600 to $334,400.

g. A 13-cm (5-in.) soil-cement cap - $209,440 to $321,440.

h. A 30-cm (5-in.) lime-stabilized cap - $209,440 to $321,440.

i. A 30-mil PVC membrane cap - $388,800 to $575,500.

The cost of constructing a drainage field above any of these caps will range between $43,600 and $87,000.

Unit cost items 2, 7, 10, 11, 18, 19, 20, 25, 26, 45, 46, and 47 were used in these calculations (see Appendix).

The costs of revegetating these surfaces and constructing diversion ditches, if required, must also be considered (see sections on Revegetation and Contour Grading).

Evaluation

Advantages--

1. Surface seals can be installed easily and economically.

2. Contractors with equipment for major earthmoving projects are available throughout the United States.

3. Fly ash may be available free of charge.

4. Soil-cement and lime-stabilized soil construction is relatively inexpensive and can be accomplished with locally available equipment.

5. Soil-cement seals do not have to be covered with soil.

6. Lime-stabilized soils can withstand some settlement without rupture.

7. Bituminous paving can be used to cover large areas rapidly.

8. In landfills where subsidence potential is minor (i.e., those with shallow, old well-compacted wastes), no further maintenance will be required.

9. Long service life is anticipated.

10. Membrane seals can withstand some settlement.

Disadvantages--

1. The cover and seal are subject to settlement and/or subsidence within the landfill.

2. Vegetation will require maintenance until it has become firmly established (1 to 2 years).

3. Specific sealing materials:

   a. Natural clay deposits may not be available.

   b. Fossil-fueled energy stations are not located in all parts of the country to supply fly ash.

c. Heavy metals in fly ash can be mobilized by precipitation and cause pollution.

d. Soil-cement caps may rupture with settlement of the landfill.

e. Membrane materials are expensive.

4. Large quantities of borrow material may be necessary to establish required slopes on the landfill surface.

5. Gas venting must be provided with all surface seals.

Recommendations

This method when properly maintained can eliminate almost all infiltration from precipitation into a landfill. Eventually, this will eliminate further leachate generation from infiltration. Surface and subsurface discharges of leachate will be minimized and therefore more easily attenuated by the environment.

References

For further discussion, see references 13 through 21.

REVEGETATION

Description

Revegetation of a completed landfill helps to physically stabilize the earth material and reduce infiltration. This method can be effective as long as there is adequate rainfall to support plant growth. Although vegetation retards surface runoff, it serves to minimize erosion of the cover material by wind and water. By stabilizing the earth materials, vegetation helps to reduce infiltration of precipitation into the landfill. It also seasonally reduces infiltration by intercepting and evapotranspiring some of the precipitation. A subsidiary benefit is that vegetation enhances the appearance of the site.

Establishing vegetation on a landfill site first involves covering the compacted municipal refuse with a suitable, fertile soil at least 0.6 m (2 ft) thick. The soil preferably should be a clay loam or silt loam. Sandy loam or soils that are excessively well drained should be avoided as they will allow increased infiltration of precipitation into the landfill. The cover material must have sufficient nutrients to support vigorous plant growth. If these do not occur naturally, soil conditioners such as organic compost, properly balanced chemical fertilizer,

or digested sewage sludge can be added to attain a satisfactory nutrient level. If sludge is considered for use as a soil conditioner, it will be important to consult State regulatory agencies regarding any restrictions or conditions for its use. The organic materials are preferred because they improve soil structure and because the nutrients are released more slowly and remain in the soil far longer than chemical fertilizers.

Prior to planting, the surface must be prepared by grading, harrowing, discing, or raking. If organic materials are used, they must be spread over the surface prior to discing so that they can be worked into the top 5 to 10 cm (2 to 4 in.) of the soil to provide a supportive seed bed. If a chemical fertilizer is used it can be applied either with the seed or after plant growth has been established, depending on the type used.

The chosen mixture of seeds and soil supplements can be hydroseeded, that is, sprayed onto the landfill surface in a water mixture. Hydroseeding is the least expensive and the most cost-effective method of seeding a landfill. Following the seeding, a mulch consisting of hay, straw, or wood cellulose can be blown onto the surface to stabilize it while the seeds germinate. On steeper slopes, netting or pegging may be necessary to hold the seeds, soil, and mulch in place until growth is established (1 to 2 years).

In order to determine types of vegetation that would be suitable for a particular site, soils analyses must be conducted. Investigations should be made of the soils used for cover, their pH and fertility, and the slopes of the areas to be covered. Methods for performing these analyses are generally available from County Soil Conservation Services.

Vegetation that develops a dense but shallow root system is more effective both in surface stabilization and seasonal infiltration reduction than vegetation with deeper, less dense roots. Grasses native to the area are the most commonly used type of vegetation because they establish quickly, especially on fertile soils, and are easy to maintain. Some that have been successfully used on landfill sites include most hay and meadow grasses, perennial rye, wild-rye, timothy, bentgrass, Bermuda-grass, Bromegrass, and tall meadow oatgrass. Grassland agriculture information is generally available through local agencies of the U.S. Department of Agriculture.

Legumes, such as crown vetch and clover, and crops, such as alfalfa, are useful in stabilizing areas that slope away from the landfill (slopes of greater than 20 to 30 percent) and areas surrounding the fill.

In areas with more than 63 to 76 cm (25 to 30 in.) of precipitation per year, grass mixtures are recommended on relatively flat lands and grass/legume mixtures on steeper slopes.

Trees and large shrubbery are not recommended for vegetating landfills because the soil mantle over the refuse is generally not thick enough to sustain their root systems. If the roots penetrate the refuse, the vegetation may be killed by gas. A thicker soil cover than the average 0.6 m (2 ft) [i.e., 0.9 to 1.2 m (3 to 4 ft)] would be required if trees were to be planted on the completed landfill.

In arid parts of the United States where the climate is not generally suitable for growing grasses or legumes, native plants such as creosote bush or salt cedar can be established on the completed fill. In these areas of the country, water erosion and infiltration are not as much of a year-round problem but both may be severe seasonally. Vegetation can be especially useful in these areas to reduce wind erosion.

A routine maintenance program should be developed for the first several years after landfill revegetation. Such a program should provide for repairing cracks in fill areas due to uneven settlement, reseeding and fertilizing as necessary on the repaired areas or on the entire surface if the original ground cover was an annual variety, and preventing major erosion and surface water ponding that could provide insect breeding sites and/or areas of increased infiltration.

Costs

On slopes of less than 12 percent, with a mixture of 20 percent perennial ryegrass, 30 percent red fescue, and 50 percent Kentucky bluegrass sown at a rate of 11 kg per 1,000 m^2 (21 lb per 1,000 yd^2) with hydroseeding and soil supplements consisting of pulverized agricultural lime at 432 kg per 1,000 m^2 (800 lb per 1,000 yd^2), urea-form fertilizer (38-0-0) at 27 kg per 1,000 m^2 (50 lb per 1,000 yd^2), and commercial fertilizer (10-20-20) at 104 kg per 1,000 m^2 (192 lb per 1,000 yd^2), costs will be approximately $0.12 to $0.18 per m^2 ($0.10 to $0.15 per yd^2).

For slopes of 12 percent or steeper, using a mixture of 45 percent preinocculated crown vetch and 55 percent annual ryegrass sown at a rate of 5 kg per 1,000 m^2 (9 lb per 1,000 yd^2) with the same soil supplements as above, costs will range from $0.12 to $0.18 per m^2 ($0.10 to $0.15 per yd^2). As an alternative, crown vetch crowns can be used. Crown vetch crowns [started plants in 8-cm (3-in.) pots] cost from $0.25 to $0.35 each and are planted at a rate of 1.2 per m^2 (1 per yd^2) on steep slopes where a rapid cover is required.

Mulching with straw or hay at a rate of 540 kg per 1,000 m^2 (1,000 lb per 1,000 yd^2) costs between $0.06 and $0.12 per m^2 ($0.05 and $0.10 per yd^2). Mulching with wood cellulose, which is often used on steeper slopes, costs between $0.12 and $0.24 per m^2 ($0.10 and $0.20 per yd^2).

Costs of seeding and mulching the hypothetical 4-hectare (10-acre) landfill with slopes of less than 12 percent will range from $7,300 to $12,000. Seeding and mulching of a 4-hectare (10-acre) landfill with steeper slopes will cost between $12,000 and $26,600.

The unit cost items used in these calculations are items 29 and 30 (see Appendix).

Evaluation

Advantages--

1. Vegetation stabilizes the final cover material and helps minimize erosion.

2. It seasonally reduces infiltration into the landfill.

3. It enhances the appearance of the site.

4. The method is inexpensive and cost-effective.

5. Procedures are uncomplicated and equipment is minimal.

Disadvantages--

1. Vegetation requires 1 to 2 years to develop an established root system. Inadequate cover soil fertility or settlement of the landfill can interfere with the establishment of vegetation.

2. Initial erosion control may be difficult until a sufficient amount of vegetation is in a stage of vigorous growth to stabilize the soil.

3. In stepped landfills, leachate breakouts can kill vegetation.

4. Gas venting provisions must be made to prevent gas migration which could kill vegetation.

Recommendations

Ground preparation and seeding are essential parts of closing or upgrading a landfill. In flat areas, seeding should be completed between March 1 and June 1 or between August 1 and October 1. Sloped areas can be seeded (with legumes) at any time of year except during September and October.

The use of trees or shrubs on newly covered landfills is not recommended; their deep root systems can penetrate the refuse and either break the cover, kill the plant, or both. The plants that can be established in arid areas nearly always have deep root systems. Therefore in arid areas unless the cover materials on the landfill are deep the site should be left to volunteer vegetation.

Vegetation is an inexpensive and cost-effective method of stabilizing the surface of a landfill and of reducing leachate generation to some degree during the local growing season. When used as part of a properly managed leachate control program, revegetation has been shown to be an effective landfill completion method.

References

For further discussion, see references 7 through 12 and 22 through 34.

SECTION 3

GROUNDWATER CONTROL

Where the landfill extends below the water table, groundwater flows through the landfill and produces considerable quantities of leachate. Most of the areas in which this occurs are underlain by unconsolidated materials and have groundwater at relatively shallow depths. In such cases, a physical barrier can be constructed to prevent movement of groundwater through the refuse. A properly constructed groundwater barrier will lower the water table in and around the landfill so that the refuse is no longer saturated and leachate generation is reduced.

This section presents methods of constructing a barrier on the upgradient side or the bottom of a landfill to control groundwater movement. These methods have considerable potential for reducing leachate generation in areas where the landfill extends below the water table and for isolating the disposed wastes when used in conjunction with top sealing methods.

BENTONITE SLURRY-TRENCH CUTOFF WALL

Description

A slurry-trench cutoff wall is an underground water barrier used to prevent horizontal subsurface movement of leachate away from a landfill. Essentially, the construction process entails digging a trench, filling it with bentonite slurry as excavation progresses, and backfilling the slurry-filled trench with the excavated material. The bentonite slurry supports the trench sides during excavation. Figures 5 and 6 show slurry-trench cutoff wall construction at the hypothetical landfill. The wall acts as a barrier to divert groundwater flow beneath and away from the landfill. A properly designed cutoff wall lowers the water table so that it no longer flows through the landfill. Encircling the landfill, while effective, may not be necessary.

The slurry-trench cutoff wall can lower the water table in the landfill by (1) providing a complete seal by extending the cutoff wall to an impermeable layer, or (2) by increasing the length of the groundwater flow path and hence the energy loss as shown in Figure 6. In the latter case, the cutoff wall forces the groundwater to flow a longer distance beneath the wall and

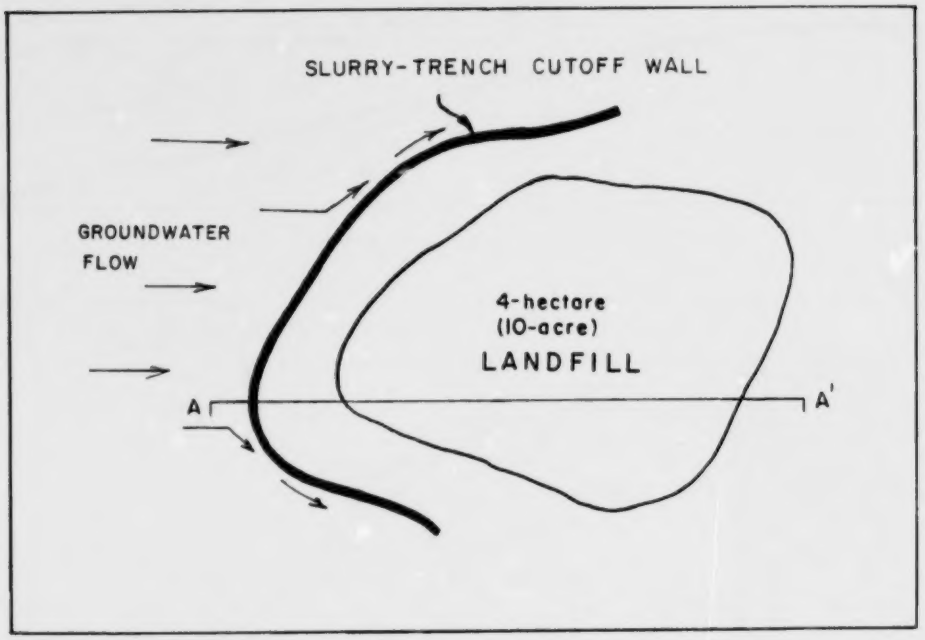
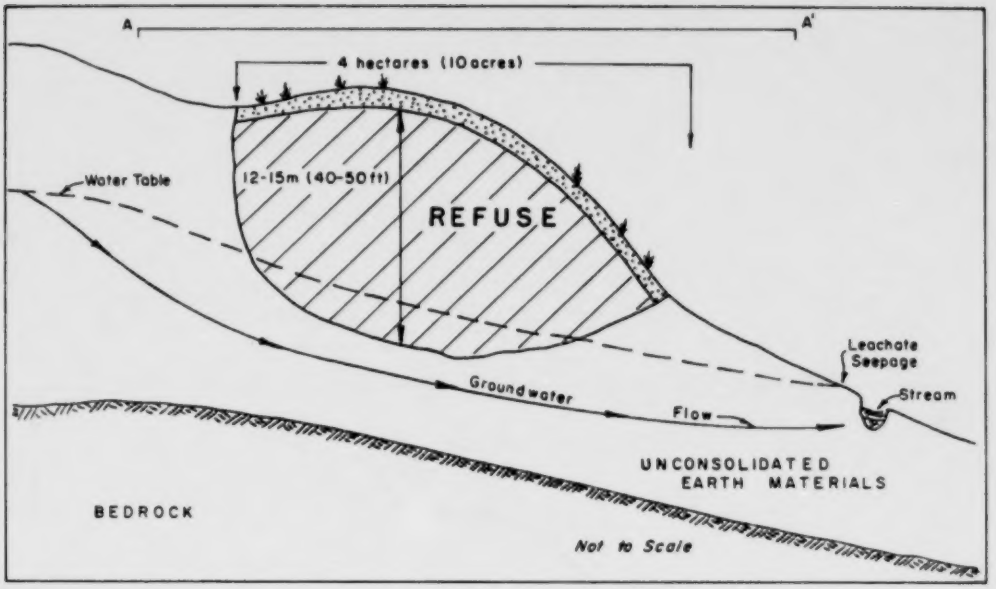
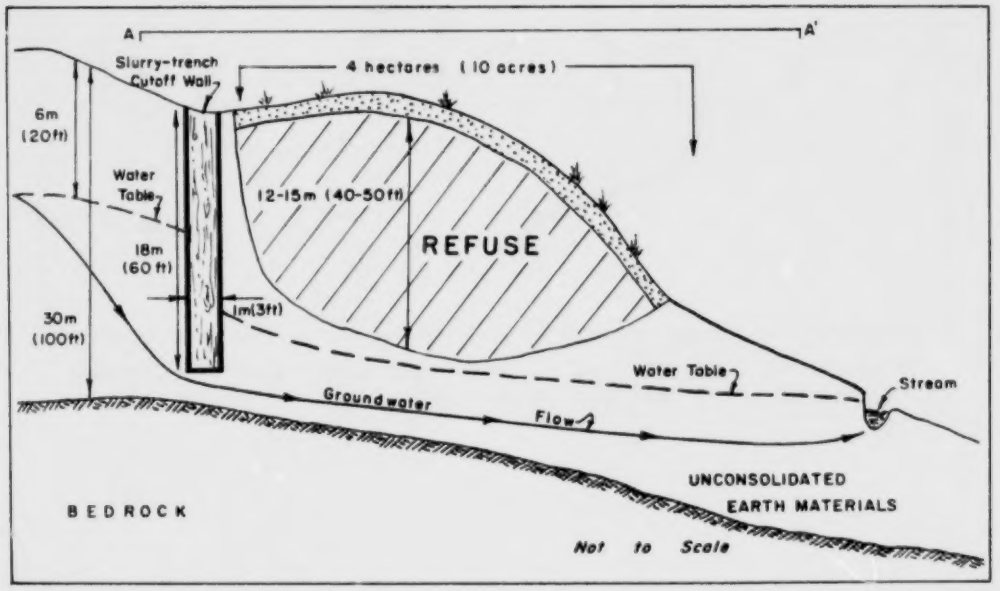


Figure 5. Plan view of semicircular slurry-trench cutoff wall around upgradient end of landfill.



(a)



(b)

Figure 6. Cross section of landfill before (a) and after (b) slurry-trench cutoff wall installation.

also diverts it laterally around the site. As water flows under the wall, it loses energy and therefore does not rise as high on the downgradient side as it would without the cutoff wall. The energy loss is represented by the gradient (slope) of the water table. The cutoff essentially lengthens the aquifer through which the water flows (see Figure 6). The lowering of the water table on the downslope side of the cutoff wall is equal to the increase in the effective length of the aquifer times the gradient (energy loss) over that distance. There will also be some reduction in water table elevation due to diversion of water around the landfill because the aquifer will have a smaller cross section and therefore less carrying capacity (see Figure 6). The length and depth of the trench required must be determined by the depth to groundwater and the type of earth materials underlying the particular landfill. A slurry-trench cutoff wall can be constructed with equipment in general use throughout the construction trade. Deep trenches can be excavated with a clamshell bucket or dragline bucket, and shallow trenches with backhoe/pull-shovel equipment. Trenches to depths of 25 m (80 ft) have been successfully completed.

Sodium bentonites, which are natural clay substances mined in Wyoming, South Dakota, and Montana, are typical materials used for constructing slurry-trench cutoff walls. When mixed in water, sodium bentonite becomes sheathed in a protective film of water molecules which causes the clay particles to swell. When the water is absorbed, the effective diameter of the particles is increased and, at the same time, a portion of the water in which the clay is suspended is inactivated. There is a resultant increase in the density of the mixture, making the specific gravity greater than that of water.

When placed in the trench, the slurry enters any exposed voids in the walls. The hydrostatic pressure created by the slurry forces the water from the voids, and the bentonite particles begin layering within and around them, forming a cake or diaphragm that completely chokes the openings. As the diaphragm builds up, it becomes impervious to penetration by groundwater, and water loss from the slurry through the trench wall decreases. The diaphragm prevents sloughing of the trench walls, and the outward pressure of the slurry prevents cave-ins.

The bentonite slurry introduced into the trench generally should weigh between 1,041 and 1,121 kg/m^3 (65 and 70 lb/ft^3). This density will increase during excavation because fine particles tend to become suspended in the slurry. The slurry must be premixed in a batch plant using a ratio of approximately 1 part bentonite to 12 parts water. The density of the slurry can be maintained at the desired levels by recirculating it through a recovery system when it becomes too heavy, and by adding more bentonite to the slurry when it becomes too light.

After excavation has begun, and as soon as it reaches the groundwater table, the slurry should be introduced into the trench. The level of the slurry should be maintained above the groundwater table as the excavation proceeds to the desired depth.

During trench excavation, the excavated material which has been soaked by the slurry is cast near the trench to allow excess slurry to drain back into the trench. The backfill material is then deposited back into the trench 60 to 150 m (200 to 500 ft) behind the excavation operation. Backfilling can be accomplished with a bulldozer or front-end loader. As the backfill material drops through the slurry in the trench, the bentonite layering or caking action takes place throughout the thickness of the slurry-trench mass to establish an effective cutoff wall impervious to groundwater. The displaced slurry is then reclaimed and processed for reuse. The backfilled trench does not need compaction.

Costs

A slurry trench 18 m (60 ft) deep and 1 m (3 ft) wide will range in cost between $294 and $495 per lineal foot complete in place. To construct a semicircular cutoff wall 518 m (1,700 ft) long around the upgradient end of the 4-hectare (10-acre) landfill will cost between $499,800 and $841,500, complete in place. Unit cost items used in these calculations are items 2, 6, and 13 (see Appendix).

Evaluation

Advantages--

1. Construction methods are simple.

2. Adjacent areas will not be affected by groundwater drawdown.

3. Bentonite is a mineral and will not deteriorate with age.

4. Leachate-resistant bentonites are available.

5. Once the cutoff wall is constructed, no further action or maintenance will be required.

Disadvantages--

1. The cost of shipping bentonite from the west to the site must be considered.

2. Several aspects of the construction procedures are patented and will require a license.

3. In rocky ground, over-excavation will be necessary because of boulders.

4. Common bentonite deteriorates when exposed to high ionic strength leachates.

Recommendations

This method can be effective in rerouting the flow of groundwater, preventing subsurface infiltration, and containing leachate generated in the landfill. Ideal conditions for effective use of a slurry-trench cutoff wall include a relatively shallow water table, an aquifer of moderate permeability, and a relatively shallow depth to bedrock or other aquifer. Contour grading and revegetation of the landfill surface to promote runoff of precipitation and minimize surface infiltration is recommended (see Contour Grading and Revegetation sections).

References

For further discussion, see references 35 through 46.

GROUT CURTAIN

Description

A grout curtain is created by injecting solutions or water/solid suspensions under pressure into soils and underlying earth materials as a groundwater barrier. The grout solution fills the voids in the soil and thereby minimizes or stops the flow of water.

In landfill neutralization, the grout is injected vertically to predetermined depths around the upgradient end of the landfill to create a curtain or wall of grout which diverts groundwater flow as shown on Figure 7.

The type of grout must be selected on the basis of the soils and geologic conditions present at the landfill. Geotechnical investigations are a critical phase of grout curtain projects. Accurate test borings, core sampling, and laboratory analyses for porosity, hydraulic conductivity, and connected pore volume must be conducted to determine the best grouting materials and methods to be used under the existing site conditions.

The most common types of grout are cement, bentonite, and chemical. Several more specialized grouts are epoxy resins, silicone rubbers, lime, fly ash, and bituminous compounds. Each grout can be used to fill a certain sized void in the earth materials present. The permeability of the soil will determine the type of grout that can be injected into the soil pores. Figure 8 indicates the types of grout that will be effective in various soils, based on their effective grain size. Combinations of these grouts may be used to seal different types of soils encountered at the site.

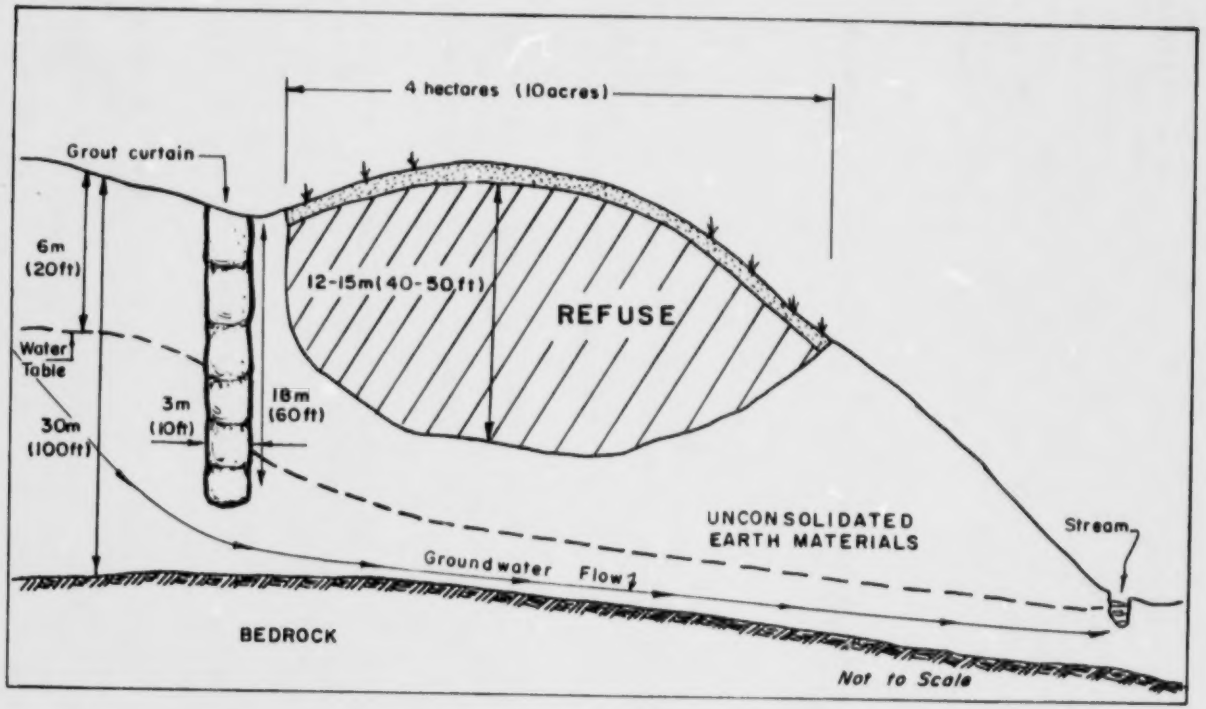


Figure 7. Cross section of grout curtain at landfill.

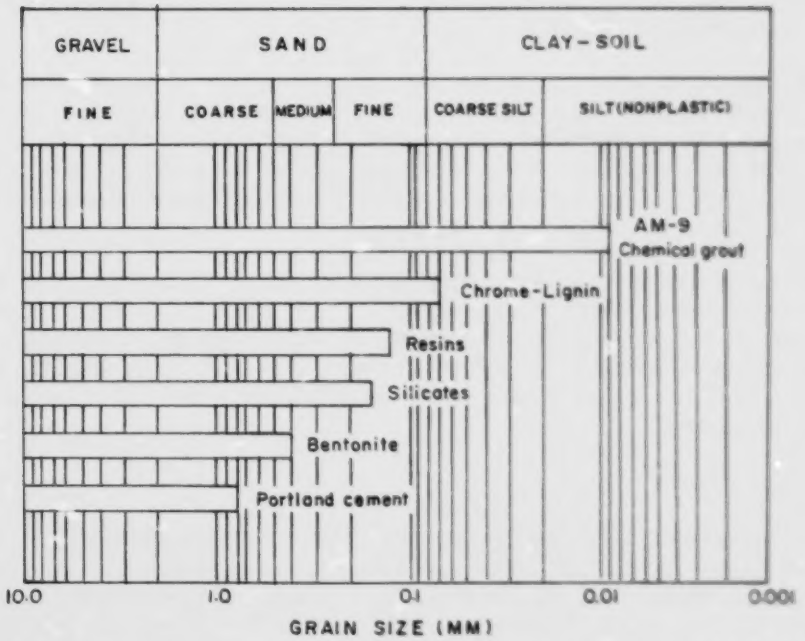


Figure 8. Soil limits of grout injectability (from American Cyanamid Co., reference 48).

Prior to use, the selected grout mixture should be tested by injection into a prepared soil sample from the site. The flow rates of the grout through the soils should be measured under different pressures. Soil permeabilities should also be measured before and after the grouting to determine its effectiveness. (Test procedures are detailed in reference 47.)

Once the grout has been selected and tested, the curtain can be designed. The curtain is formed by arranging two or three rows of pipes offset from each other in a grid pattern over the area to be sealed (see Figure 9), and injecting grout through the pipe at successive depths. The resulting curtain is shown in Figure 10. Grout pipe is commonly extended to a maximum of 15 to 18 m (50 to 60 ft). Deeper injections may require heavy-duty driving equipment.

The spacing in the grid pattern can be determined by formula so that when injected, the grout will spread outward at least half the distance between the pipes before setting to fill the pore spaces throughout the grouted area. Thus, a continuous wall will be formed. The preliminary grout and soil tests will be helpful in determining pipe spacing.

The rate of grout injection will be a function of the type of grout and the subsurface conditions at the site. Cement grout sets up in approximately 4 hours, whereas some chemical grouts set up within seconds after placement. A volume of 11 to 19 liters/min (3 to 5 gal/min) can be assumed as an average rate for grout injection.

Costs

When several grouts are suitable for a particular application, the cost of grout may determine the order of preference. Table 1 indicates the relative cost basis of various chemical grouts compared with cement. Injected complete in place, portland cement grout costs between $142 and $357 per m^3 ($4.00 and $10.00 per ft^3).

To install a 518-m (1700-lineal ft) cement grout curtain cutoff wall in a horseshoe configuration on the upgradient side of the 4-hectare (10-acre) landfill to a depth of 18 m (60 ft) will cost between $801,300 and $2,003,000, using a two-row grid pattern with pipes on 1.5-m (5-ft) centers, and injecting a portland cement grout with a 5 to 1 water-cement ratio in coarse sand with a porosity of 25 percent. Unit cost item 14 was used in these calculations (see Appendix).

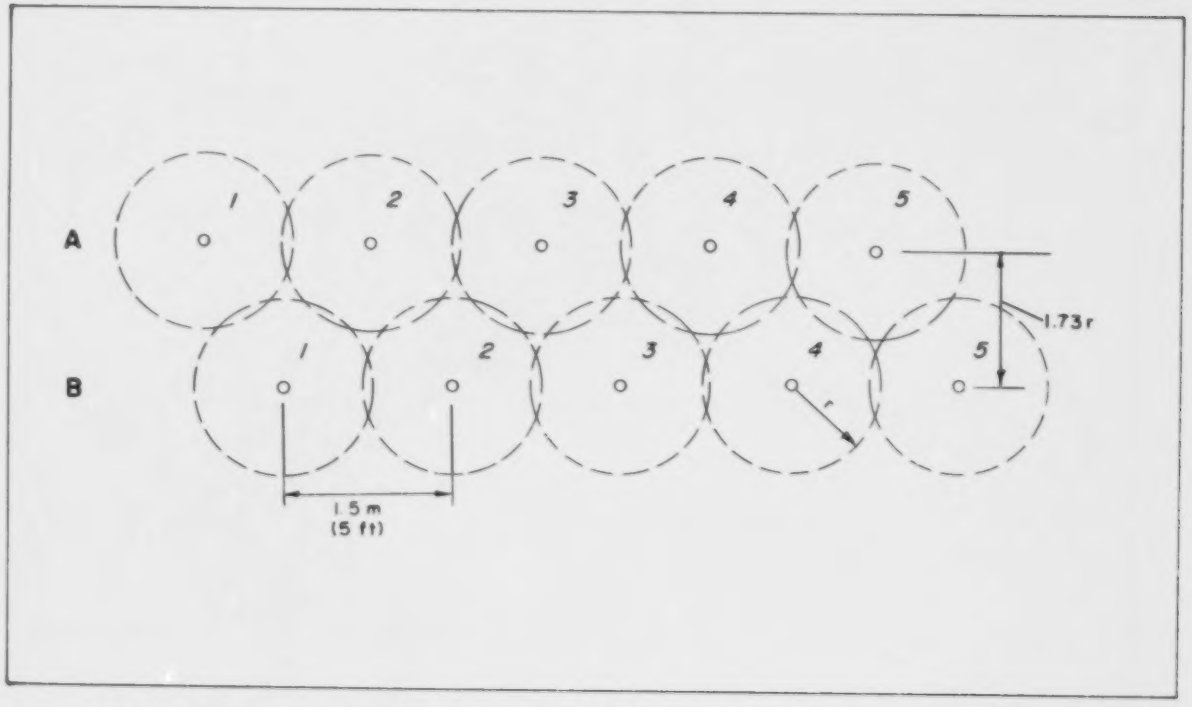


Figure 9. Typical two-row grid pattern for grout curtain.

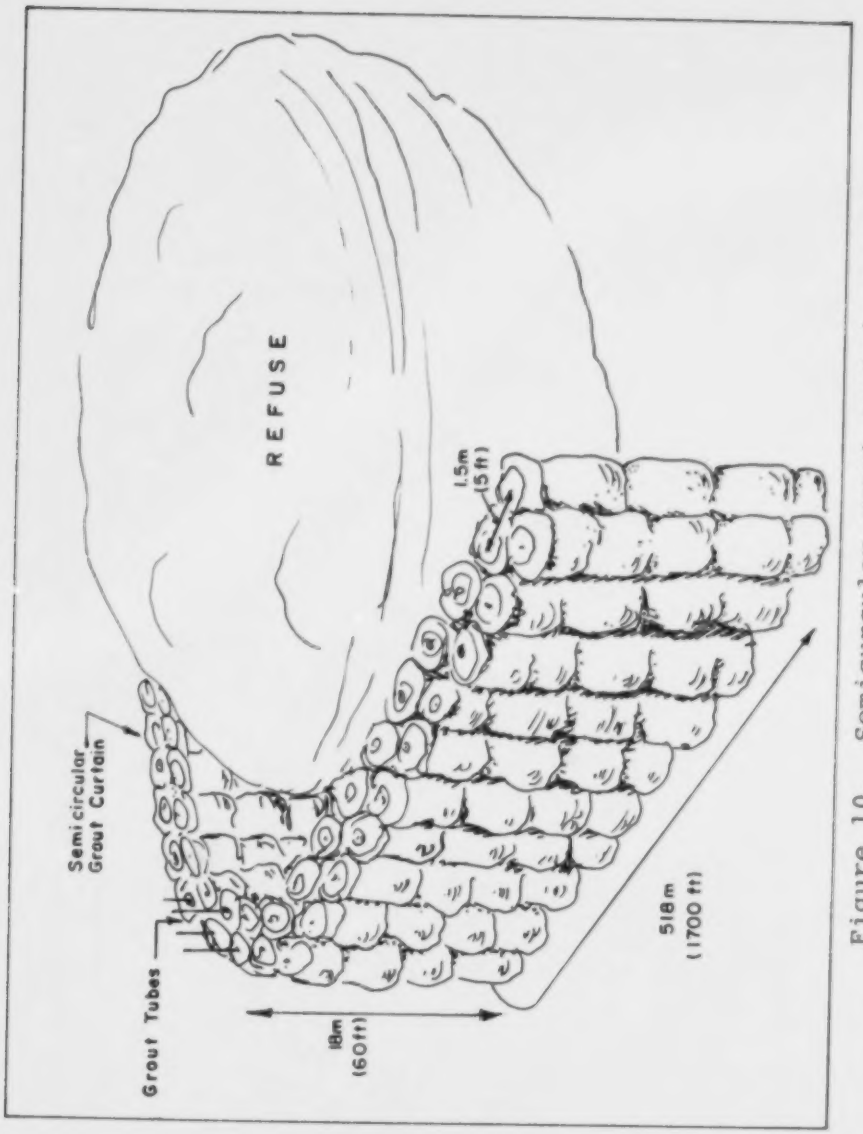


Figure 10. Semicurcular grout curtain around upgradient end of landfill.

TABLE 1. RELATIVE COSTS OF GROUT*

Type of Grout	Basic Cost Figure
Portland cement	1.0
Silicate base - 15 percent	1.3
Lignin base	1.65
Silicate base - 30 percent	2.2
Silicate base - 40 percent	2.9
Urea formaldehyde resin	6.0
Acrylamide (AM-9)	7.0

*Base unit = 1.0. Under a given set of conditions, where portland cement grout costs 1.0 times $/unit, other types of grout will cost the given figure times $/unit.

Evaluation

Advantages--

1. When designed on the basis of thorough preliminary investigations, curtain grouting can be very successful.

2. The method is well established; it has been in use for over 100 years in construction and stabilization projects.

3. There are many kinds of grout to suit a wide range of soil types.

Disadvantages--

1. Grouting is only effective in soils with permeabilities of 10^{-5} cm/sec or greater.

2. Some grouting techniques are proprietary.

3. Because grouting involves subsurface construction, the procedure requires careful planning and pretesting. Methods of ensuring that all voids in the wall have been effectively grouted are not readily available.

4. Chemical grouts are expensive.

Recommendations

An in-depth field and laboratory investigation is essential in the design of an injection curtain cutoff wall.

Grouting is considered a feasible solution in consolidated sand or cohesionless soils. Chemical grouts must be used in fine sands and silts to a permeability of 10^{-5} cm/sec. Grouting alone cannot be considered a cure-all. It is recommended that this method be combined with other corrective measures such as grading, seeding, and mulching to minimize surface infiltration.

References

For further discussion, see references 38, 41, and 47 through 51.

SHEET PILING CUTOFF WALL

Description

Construction of a sheet piling cutoff wall involves driving lengths of steel sheet piling permanently into the ground with a pile-driving hammer. Lengths of sheet piling over 30 m (100 ft) have been successfully placed.

Sheet piling is a web section of steel with an interlocking device along both edges, consisting of either a socket end or bowl-and-ball end. Various shapes and weights of steel sheet piling are available in standard lengths for use in different types of earth materials. The most common shapes are the Z-type, pan or hat type, and straight types. Weights of sheeting range from 107 kg/m^2 (22 lb/ft^2) for the pan type to 185 kg/m^2 (38 lb/ft^2) for the Z-type.

The sections are assembled before being driven into the ground. When first installed, the sheet piling wall is not watertight due to mill tolerances in the interlocking edges. With time, these edges self-seal with the fine sediment carried by seeping water.

The sheet piling wall shown in Figure 11 is designed to retard the flow of water under and through the landfill. If the soils were extremely permeable, the groundwater would rise too quickly under the landfill and it would be necessary to extend the piling to bedrock to dewater the landfill.

The service life of steel sheet piling at installations around the country has far exceeded the theoretical estimate of performance, especially in soils where adverse conditions and chemicals have been present. Corrosion of the metal does not appear to be a factor in causing failures in the structure. Inspections of pilings in place ranging in age from 7 to 40 years, in soil types ranging from well-drained sands to impervious clays, with soil resistivities ranging from 300 ohm-cm to over 50,000 ohm-cm, and soil pH ranging from 2.3 to 8.6 indicated that the type and amount of corrosion was not sufficiently significant to affect the material's strength or useful life.

Cathodic protection is suggested for submerged piling. Properly spaced sacrificial anodes will provide adequate protection.

Costs

A steel sheet piling cutoff wall installed at the upgradient end of the hypothetical landfill will have soil material on both faces; therefore, a light section will be adequate in this case. The lightest section made is designated PMA 22 (AISI standardized section designation) and weighs 107 kg/m^2 (22 lb/ft^2).

Costs were developed assuming a sheet piling cutoff wall 518 m (1,700 lineal ft) long and 18 m (60 ft) deep. The sheet piling distributor closest to the east coast hypothetical landfill is located near Buffalo, New York. Material costs (F.O.B. plant) are $37.00 per 100 kg ($16.80 per 100 lb). Truckload permits are $24.75 and shipping charges are $3.65 per 100 kg

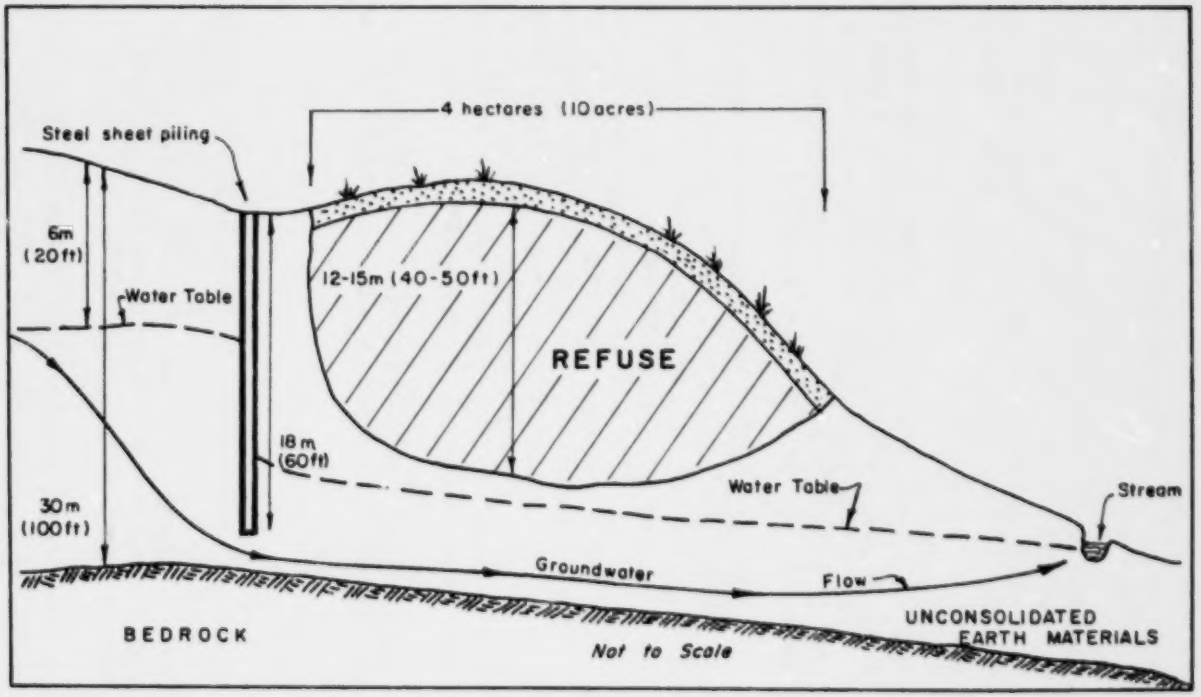


Figure 11. Cross section of sheet piling cutoff wall at landfill.

($1.65 per 100 lb) [$7.25 per 20-tonne load ($660 per 20-ton load) from Buffalo, New York to the Philadelphia area] for total shipping charges of $38,450.

Total costs to construct and install the sheet piling cutoff wall then will be $650,500 to $956,500, complete in place. Unit cost item 22 was used in these calculations (see Appendix).

Evaluation

Advantages--

1. Construction is not difficult; no excavation is necessary.

2. Contractors, equipment, and materials are available throughout the United States.

3. Construction is relatively economical.

4. Once the cutoff wall is installed, no further maintenance or action will be required.

5. Steel can be coated for protection from corrosion to extend its service life.

Disadvantages--

1. The steel sheet piling initially is not watertight because of manufacturing tolerances.

2. Driving the piling through ground containing boulders is difficult.

3. Exotic chemicals, if present, may attack the steel.

Recommendations

A steel sheet piling cutoff wall is a maintenance-free means of preventing groundwater flow through a landfill. To minimize surface infiltration, it is recommended that the landfill also be contour graded and revegetated.

References

For further discussion, see references 52 through 57.

BOTTOM SEALING

Description

This neutralization alternative involves creating a bowl-shaped bottom seal beneath the site and isolating the landfill from the groundwater (see Figure 12). The seal is constructed by pumping or pressure-injecting grout under the existing land-

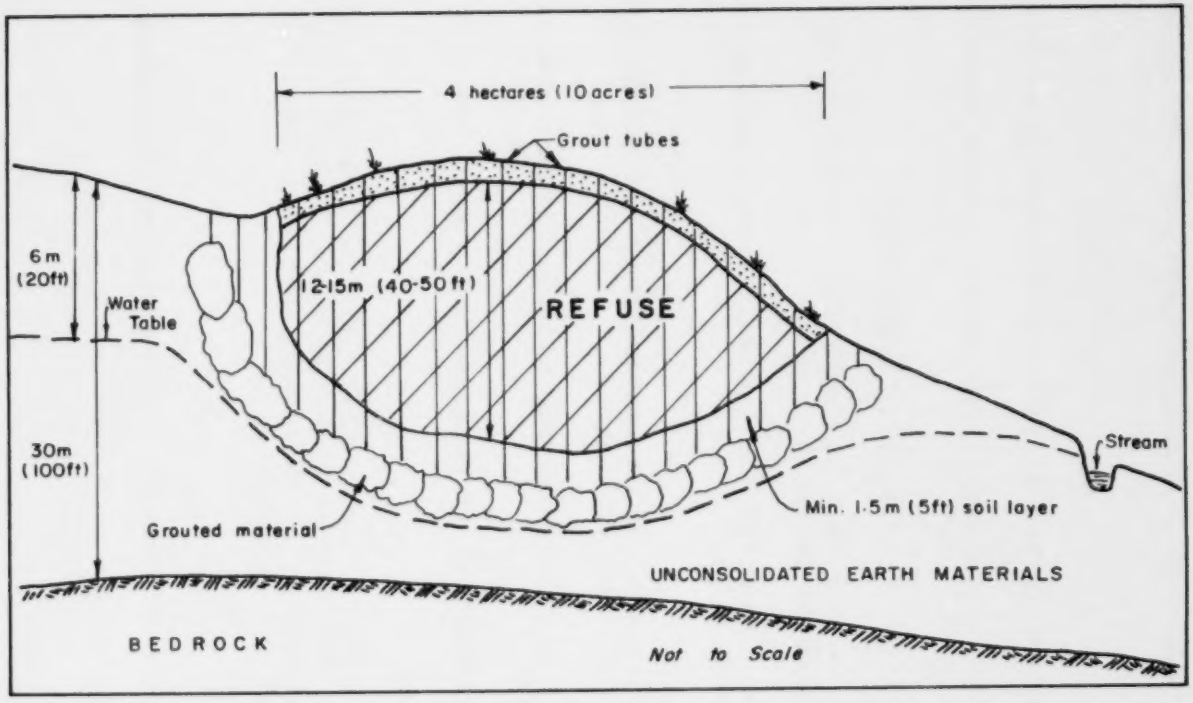


Figure 12. Cross section of grouted bottom seal beneath landfill.

fill through tubes placed through the fill at regular intervals. Portland cement grout, leachate-resistant bentonite slurry, or chemical grout can be used. Some methods of pressure grouting have been patented.

Initially, exploratory boreholes must be drilled to determine the limits of the landfill both vertically and horizontally. The entire site must be gridded with permanent survey references. The grid pattern can be based approximately on 1.5- to 1.8-m (5- to 6-ft) centers. Exploratory boreholes should be drilled on 30-m (100-ft) centers to determine the lowest elevations of the refuse; and a contour map of the landfill bottom should be prepared. The boreholes should be extended at least 6 m (20 ft) below the refuse to sample the underlying material.

The material being grouted, e.g., clay, sand, silt, gravel, must be tested and identified so that the appropriate type, amount, and application rate of the grout can be determined. In the seal installation, the grout tubes are extended from the surface in a grid pattern to below the landfill. A layer of soil a minimum of 1.5 m (5 ft) thick or the thickness of the grout liner should be left between the grouted material and the refuse to allow for irregularities in the bottom of the landfill. The liner can be between 1.2 and 1.8 m (4 and 6 ft) thick. The grout is pumped under pressure through the tubes and driven into the voids in the soil. It then hardens into a permanent liner.

The bowl-shaped seal will be effective in containing leachate in the landfill. If extended high enough, it can prevent groundwater from flowing into the fill where the water table is above the bottom of the landfill. The leachate contained in the fill can then either be pumped out and treated, or remain isolated in the landfill.

Further leachate generation must be controlled, however, so as not to exceed the capacity of the bowl. The landfill surface should be contour graded and revegetated to promote surface runoff and minimize vertical infiltration of precipitation.

Costs

The costs of constructing a grout bottom seal will vary depending on the permeability of the grouted materials. To construct a 1.2-m (4-ft) thick portland cement bottom liner under the entire 4-hectare (10-acre) landfill will range in cost as follows depending upon the soil permeabilities: with 20 percent voids, $1,115,000 to $2,786,000; with 30 percent voids, $1,672,000 to $4,180,000.

A 1.8-m (6-ft) thick liner under the landfill will range in cost as follows: with 20 percent voids, $1,667,000 to $4,166,000; with 30 percent voids, $2,500,000 to $6,250,000.

The cost of the exploratory boring program based on the recommendations presented in this section will range between $7,600 and $25,000.

These estimates are based on unit cost items 14 and 24 (see Appendix).

Evaluation

Advantages--

1. Grouting has been a standard practice for many years and is very effective in gravel and sand.

2. Construction is relatively easy and can be performed at any time of year.

Disadvantages--

1. Drilling through the refuse may be difficult because of unknown materials.

2. The grout-take may be erratic when uncharted pockets of fine-grained soils are encountered.

3. Methods of determining that all voids between boreholes have been effectively grouted are not readily available. After installation, an ungrouted void would be difficult to locate.

4. Overdesign of the grout barrier is almost unavoidable because of the uncertainties involved in creating a solidified mass beneath the landfill to prevent seepage.

5. Bottom sealing has not yet been used on landfills and leachate may have a deleterious effect on the grout integrity.

Recommendations

Bottom sealing with grout is especially effective in coarse-grained soils and gravels up to depths of 90 m (300 ft). The isolation barrier formed by the grouted soil can effectively control leachate movement into the groundwater. Contour grading and revegetation of the landfill surface are recommended in support of the liner installation.

References

For further discussion, see references 38, 41, and 47 through 51.

SECTION 4

PLUME MANAGEMENT

Methods of plume management are designed to improve ground and surface water quality around a landfill by actively altering the course of leachate movement. They generally involve either the addition or removal of water by pumping or drainage from around the landfill. These methods require a continuing input of energy to the hydrologic system, usually in the form of power for pumping water. They also require continued maintenance. However, because they actively add or remove groundwater they can effect greater changes in water table elevations than can passive barriers.

The first category of plume management methods involves groundwater extraction. All groundwater extraction methods are designed to lower the water table by collecting groundwater and/or leachate. These methods are similar in purpose to subsurface infiltration barriers, passive methods of leachate control.

The second plume management category is injection, that is, the addition of water to the groundwater either to flush contaminants from the refuse or to redirect the movement of leachate. Injection is most often used to recycle the leachate removed from extraction wells back onto the refuse cell. Its other applications, such as injection/extraction barriers, would be useful in protecting an important water supply from leachate encroachment.

Plume management measures often involve leachate collection and handling (i.e., treatment, recycling, or disposal). Several methods of leachate management are discussed and evaluated in this section.

EXTRACTION

Description

There are three basic means of removing water and/or leachate from the ground: drains, well point systems, and deep well systems. Each of these systems can be used either upgradient or downgradient of a landfill. In an upgradient situation, the purpose of the system is to intercept water which would otherwise

have saturated the lower portion of the landfill and caused leachate generation. To ensure that the fill is actually dewatered by the cone of depression developed, these systems must be placed close to the upgradient end of the fill. This means that even though the upgradient system is designed to intercept mainly uncontaminated water, it might also intercept and collect some leachate. Therefore the water may not always be directly discharged to surface water. Recirculation or treatment systems may be necessary to handle contaminated groundwater.

Extraction systems located downgradient of the landfill are placed so as to intercept the leachate and groundwater as it flows from the landfill. Commonly the system is relatively shallow, unless leachate is moving downward beneath the landfill in which case the system must be relatively deep.

Drains--

The purpose of drains is to intercept groundwater and carry it away. They can be used to lower the water table a few feet or to channel and collect leachate to prevent sidehill seeps and seepage into surface water bodies (see Figure 13). Drains are widely used to reclaim swamp land for agriculture, and construction techniques for their emplacement are well developed.

Drains are constructed by excavating a trench, partially backfilling it with sand or gravel, placing either a plastic or ceramic drain tile in the sand and gravel bed, and completing the backfilling. To prevent clogging of drains by the surrounding soils, the backfill material must be only slightly more permeable than the surrounding material.

Well Point Systems--

Well point systems can be used to lower the water table several feet and/or to collect leachate. They are commonly used to lower the water table at construction sites. Well point systems have a limited radius of influence, governed by the hydraulic conductivity of the material in which they are emplaced. Suction is used for extraction in these systems, which limits the depth of extraction to 10 m (30 ft). They can provide drawdowns of up to 4.5 m (15 ft) in their immediate vicinity. In order to determine the spacing required for the wells and the effectiveness with which they can be used, a hydrogeologic study of the aquifer characteristics of the area, including a pump test, must be conducted prior to design of the system.

In the installation of well point systems, short lengths of well screen on 5- to 7.5-cm (2- to 3-in.) pipe are installed by jetting on 1- to 1.5-m (3- to 5-ft) centers in a line up- or downgradient from the fill (see Figure 14). The well points are connected to a suction header and the header is connected to a pump which evacuates the air from the well points and the header. This vacuum results in external pressure which forces the ground-

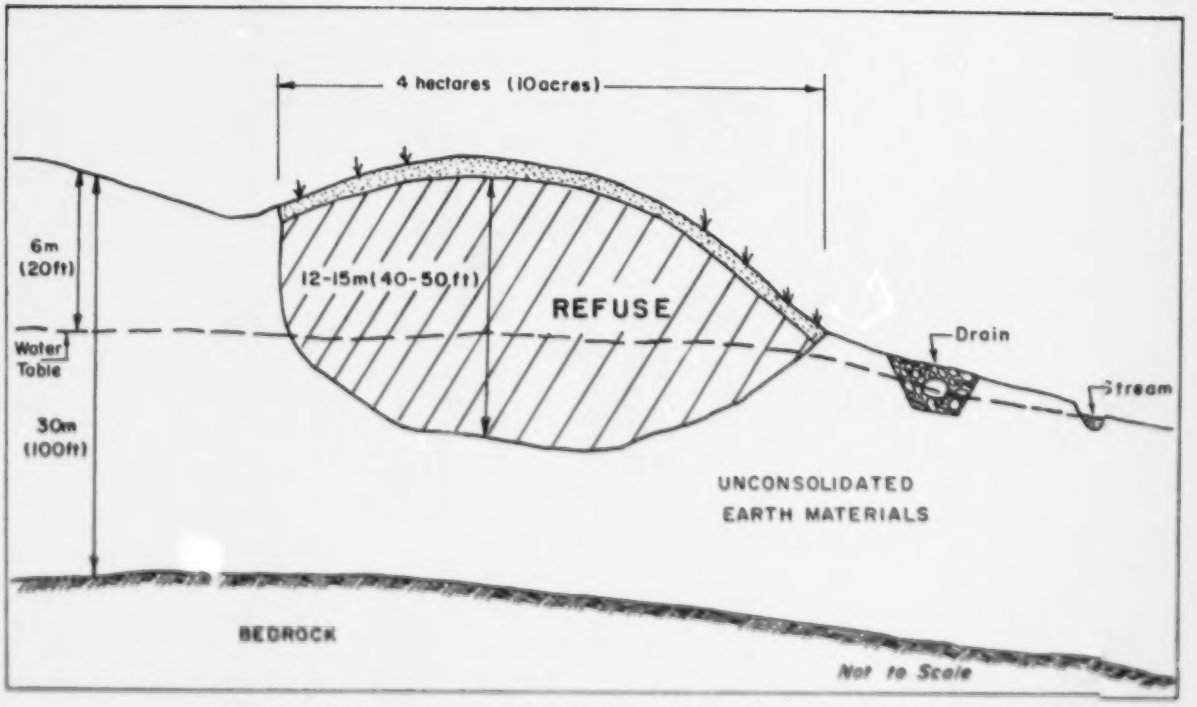


Figure 13. Cross section of drain downgradient from the landfill.

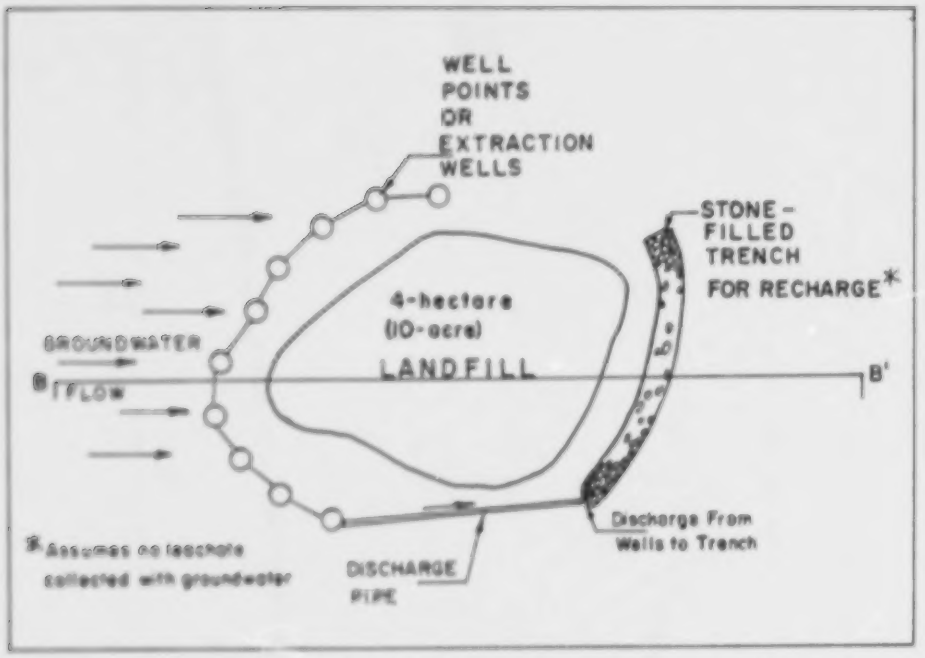


Figure 14. Plan view of well points or extraction wells used to lower the water table upgradient from the landfill.

water to flow through the well points. Since this is a vacuum-operated system, it is necessary that all portions of the well point header system be completely airtight. For permanent installation, such as at a landfill, the header would be buried in a trench, preferably below frost line. PVC is the recommended construction material for the well points and a header handling leachate. The collected water can be discharged either to a stone-filled trench for recharge to the groundwater or discharged to the surface water. If contaminants are present, leachate must be treated before discharge.

If dewatering depths of greater than 3 to 5 m (10 to 15 ft) are needed, more than one stage of well points would be necessary. The second stage of well points would be installed 2 to 2.5 m (6 to 8 ft) below the first stage.

Deep Well Systems--

Deep well systems are useful for dewatering soils in cases where a large vertical interval must be dewatered (see Figure 15). In a deep well system, each well is equipped with its own pump, and the lift is not limited to suction as in a well point system. Thus deep well systems can dewater at much greater depths than well point systems. Deep wells are capable of lowering the water table as much as 12 m (40 ft) in uniform sand. However, the initial investment in a deep well system is generally higher than in a well point system, since it requires more materials and equipment and is significantly more expensive to install.

A hydrogeologic evaluation of the aquifer, including aquifer testing, must be conducted before a deep well system can be designed. Depending on the permeability of the geologic materials, the spacing between the wells may vary from a few feet to perhaps 30 m (100 ft) with a well depth of 9 to 18 m (30 to 60 ft).

Costs

Drains--

Shallow drainage by trenches or subgrade drains costs on the order of $1,235 to $1,730 capital cost per hectare drained ($500 to $700 per acre of landfill drained), depending on the depth of placement and materials used. Labor and maintenance costs are $1,545 per year. The cost of operating the system for 20 years in current dollars is $16,900; the total cost to drain a 4-hectare (10-acre) landfill is $21,900 to $23,900.

Dewatering by Well Points or Deep Wells--

Well point systems cost $30 to $33 per m ($9 to $10 per lineal drain ft) for installation of well points and headers, plus $2,000 to $3,000 for a 19- to 25-liter/sec (300- to 400-

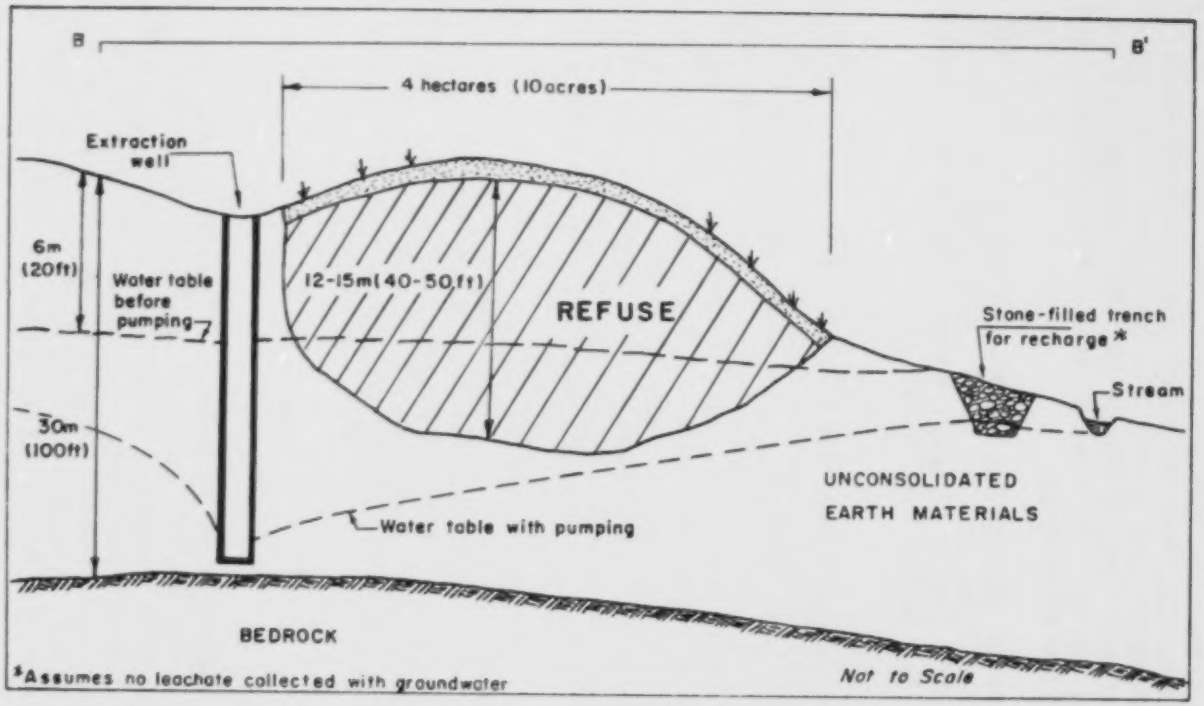


Figure 15. Cross section of extraction well at landfill.

gal/min) pump. To drain a 275-m (900-lineal-ft) area upgradient of a landfill therefore would cost approximately $12,000 (capital cost).

Deep well dewatering systems cost approximately $50 per m ($15 per ft) for a 10-cm (4-in.) PVC well plus $100 for a screen and $800 to $1,000 for a pump. Using nine 18-m (60-ft) deep wells to drain a 275-m (900-ft) front would cost $18,000 for installation of the wells and pumps plus the cost of connecting electric service.

A number of additional costs common to both well point and deep well dewatering systems are the costs of electric power, pretesting, pretest analyses, and system design and engineering.

Electric power costs for either system would be approximately $10,500 per year, based on a 32-kw (24 hp) demand at $0.07 per kWh.

Pretesting is essential to ensure proper design of any dewatering system. A test well 18 m (60 ft) deep constructed as above would cost approximately $1,000. Three piezometers at a cost of $16 per m ($5 per ft) at a depth of 18 m (60 ft) would also be necessary, at a cost of $900. A 12-hour airlift pump test at $30 per hour would cost $360 for a total approximate pump test cost of $2,000.

Analysis of the pump test by a competent hydrogeologist would cost $2,500 to $4,000, depending on the complexity of the aquifers.

System design and engineering costs would run between $5,000 and $10,000 depending on the complexity of the electrical and mechanical work and the hydrogeologic situation.

In summary, the costs for dewatering a 275-m (900-lineal-ft) area upgradient of the landfill are estimated as follows:

Well point system	$12,000
Pump test	2,000
Pump test analyses	2,500 - 4,000
System design and engineering	5,000 - 10,000
	$21,500 - $28,000 capital
Labor/year	$ 3,100
Material/year	1,080
Power/year	10,500
	$14,680 x 10.91* = $160,200

Total Present Worth: $181,700 - $188,200

Deep well system	$18,000
Pump test	2,000
Pump test analyses	2,500 - 4,000
System design and engineering	5,000 - 10,000
	$27,500 - $34,000 capital
Labor/year	$ 3,100
Material/year	386
Power/year	10,500
	$13,986 x 10.91* = $152,600

Total Present Worth: $180,100 - $186,600

*The present worth calculation factor is based on 6-5/8 percent interest for 20-year power, operation, and maintenance costs.

These calculations are based on unit cost items 31 through 37 and 39, 43, and 44 (see Appendix).

Evaluation

Advantages--

1. Construction methods are relatively simple.
2. Actual removal of water and/or leachate from the landfill is effected.
3. Groundwater resources are protected by positive action.
4. Installation is not overly expensive.

Disadvantages--

1. Power costs are high.
2. Continued maintenance is necessary to prevent system malfunction.
3. With well point systems, fairly constant supervision is required to insure that suction is maintained in the system.
4. Pumping requires a long-term commitment of both manpower and material.
5. Extracted water may be contaminated with leachate and have to be treated before it is discharged.

Recommendations

Extraction methods can be extremely effective in reducing leachate generation by groundwater or preventing leachate flow to undesired areas. They are, however, expensive and require a long-term commitment to the maintenance of the landfill. Regrading and revegetation of the landfill are recommended to reduce the quantity of leachate generated by infiltration.

References

For further discussion, see references 58 through 67.

INJECTION

Description

The second plume management technique involves the introduction of water or leachate into the groundwater either through or around the landfill. Water or leachate may be introduced through well points or deep wells, or it may be spread on the surface in seepage beds or trenches.

The purpose of introducing clear or uncontaminated water into the aquifer is to provide a barrier to leachate movement. This technique has been used mainly to prevent intrusion of salt water into aquifers. If, for instance, the leachate plume was moving toward a municipal well field, it might be effective to create a groundwater mound between the leachate plume and the well field to redirect its course. A critical concern in creating an injection barrier is finding an alternate direction of travel for the leachate plume. The leachate must either be attenuated on its new course and mixed with groundwater to harmless concentrations, or discharged at some point where it causes no harm to the receiving water body. Deep well injection would generally only be used if a shallow, potable aquifer was underlain by a deep, highly mineralized and unusable aquifer, with good hydraulic isolation between them. In such a case, if not restricted by local law, leachate could be extracted from the shallow (potable) aquifer and injected into the deeper (non-potable) aquifer. A detailed hydrogeologic investigation is required to ensure that the leachate is contained and does not migrate or cause other contamination problems. Shallow well injection can be used to introduce leachate into the landfill itself and, as such, is discussed under the Leachate Handling section herein.

Costs

An injection/extraction barrier would cost roughly twice as much as a deep well extraction system because twice as many wells would be required in addition to transmission and control equip-

ment. Thus costs for installation of an injection/extraction barrier at the 4-hectare (10-acre) site are estimated at $35,000 to $36,000. The labor, material, and power costs would be approximately $15,000 per year plus electrical service connection fee for a present worth of $163,700 for 20 years. The total cost would be $198,700 to $199,700. (See unit cost items 34, 35, 36, 40, and 43 in Appendix.)

Evaluation

Advantages--

1. Injection into a landfill can accelerate refuse stabilization.

2. An injection barrier provides a positive means of halting the speed of leachate at any depth.

3. Deep well techniques for the design and emplacement of injection/extraction barriers are well documented.

4. Injection of leachate results in its permanent disposal.

Disadvantages--

1. Establishment of an injection/extraction barrier initially requires large amounts of water. The water may not be reusable after is is re-extracted.

2. With barriers, the plume is redirected rather than removed.

3. Initial and maintenance costs are high, especially for corrosive or hard water.

4. Careful management is required to avoid contamination of other aquifer areas.

Recommendations

Injection barriers can best be used to protect a valuable water resource when a large area is involved or when installation of a physical barrier is not possible, as in a bedrock aquifer. Regrading and revegetation are recommended to reduce infiltration and the quantity of leachate generated.

References

For further discussion, see references 64, 66, and 68.

LEACHATE HANDLING

Description

Once leachate has been intercepted and collected, it can

either be recycled through the landfill to be treated and to flush out additional contaminants or it can be treated and discharged. Recycling or flushing serves to accelerate the stabilization of the landfill so that the system can be discontinued at an earlier date. The three most widely used recycling methods are: spray irrigation, overland or at-grade irrigation, and subgrade injection or tile fields. Leachate treatment, although effective in removing the contamination, does not help prevent further leachate generation. Therefore methods of leachate treatment are not detailed in this manual.

Spray irrigation has the advantage among the three of effecting some leachate treatment during the spraying event through both aeration and infiltration through the surface soil layer. Spray nozzles are placed at 15- to 30-m (50- to 100-ft) intervals on the landfill, and effluent is periodically pumped through them onto the landfill surface.

Overland irrigation is an inexpensive, well-developed agricultural technique that uses trenches, spreading basins, or gated pipe to spread effluent. Leachate is pumped into the distribution system once or twice a week and allowed to infiltrate into the ground. With both spray irrigation and overland irrigation, an impermeably lined pond is necessary to provide storage of the leachate between irrigation events.

Subgrade irrigation through a tile field or wells, although more expensive initially than the other two, may be used continuously and has the advantage of avoiding local odor problems. Tile field construction is similar to that of a large on-lot sewage disposal system in that perforated pipe is buried in gravel-lined trenches. Very large tile fields must be subdivided into smaller units and each unit fed leachate separately. Shallow well injection systems are constructed similarly to well point extraction systems (detailed in the Extraction section).

All of these systems must be designed so that the leachate is spread evenly over the landfill. Uniform distribution of leachate in the fill will promote uniform stabilization. The rate of application must also be controlled so that the leachate does not mound too high. Generally a rate of a few inches per acre per week is adequate. If the leachate mound rises too high in the fill, the groundwater flow direction may change and the leachate could migrate away from the landfill. Careful design can prevent this problem.

Costs

The capital costs of leachate spreading and application systems range from $1,235 to $7,500 per hectare ($500 to $3,000 per acre), depending on the use of open trenches, spray irriga-

tion, or buried pipe. The present worth of the three systems is shown on Table 2.

Evaluation

Advantages--

1. Recycling accelerates stabilization of the landfill.

2. No treatment facilities are initially required for collected leachate.

Disadvantages--

1. Initial and maintenance expenses are high.

2. Above-grade systems often create odor problems.

3. Careful management of application is required.

4. Site access must be well controlled to prevent vandalism and accidents.

5. Leachate recycling may lead to increasing volumes of leachate. As a result, handling costs may increase and leachate may eventually have to be discharged to ground or surface waters.

Recommendations

Leachate recycling is useful in conjunction with leachate collection systems. Recycling is often preferable to leachate treatment and discharge because it promotes rapid landfill stabilization.

References

For further discussion, see references 60, 62, and 66.

TABLE 2. PRESENT WORTH OF LEACHATE RECYCLING SYSTEMS*

System	Capital Costs	Annual Operation and Maintenance Costs	Annual Power Costs	Present Worth	Total
Spray Irrigation (solid set)	30,900	3,500	24,500	305,500	336,400
At-grade Irrigation (gated pipe, ridge and furrow)	4,600	2,500	N/A	27,300	31,900
Subgrade Irrigation (buried pipe)	10,800	1,550	N/A	16,900	23,700

*Source: Pound, C. E., R. W. Crites, and D. A. Griffes, Costs of Wastewater Treatment by Land Application. EPA-430/9-75-003, June 1975, 156 pp. (reference 66).

SECTION 5

CHEMICAL IMMOBILIZATION

Chemical immobilization is a developing technique used to bind contaminants so that they cannot migrate and form leachate. Methods of chemical immobilization rely on the initiation of a chemical reaction which produces either a stable insoluble compound from the potential contaminants, or a chemically formed impervious membrane to stop their flow.

Chemical fixation is the application of chemicals to destroy or stabilize hazardous materials. This method can be used to immobilize the in situ landfill, or the contaminant-producing materials that have been chemically stabilized can be used as a surface seal on the landfill.

Chemical injection is the injection of chemicals into a landfill to immobilize or destroy a potential contaminant. This method involves fairly sophisticated technology and is most useful in areas where leachate formed from waste would otherwise be extremely hazardous.

CHEMICAL FIXATION

Description

The application of chemicals to destroy or stabilize hazardous materials and potential pollutants has been a common practice for many years, particularly for industrial wastes. Generally, chemical treatment is quite waste-specific. Thus, an effective system in one case may be ineffective or totally inapplicable in another. For example, the application of chlorine to destroy cyanides, the application of lime to precipitate and insolubilize fluorides, and the application of alkalis to precipitate and immobilize heavy metals are standard but waste-specific processes.

Since the early 1970s, several proprietary processes have been developed which tend to be applicable to a broader range of wastes. Some of these newer systems are more applicable to liquids and thin sludges, while others function best with heavier sludges and solids. In any case, the processes rely on the reactions of such materials as portland cement, lime, and common silicates for the encapsulation, solidification, and/or cementa-

tion of a waste material. It is these proprietary fixation methods that are addressed in this section.

Each of these processes entails the mixing of the cementation/setting/reactive agents (cement, lime, silicates, etc.) with the waste material. In the case of liquids the agent absorbs the waste; in the case of solids the agent coats the surface of the solids to cement them together. In sludges, where both liquids and solids are present, both absorption and cementation (or setting) occur. Some of these processes rely mainly on the ability of the chemical system to insulate each particle of pollutant from adjacent leaching fluids; others rely upon the formation of a relatively impermeable mass to exclude leaching fluids from passing through the waste.

The earliest commercially prominent stabilization system was a process offered by Chemfix for application to hazardous liquids and sludges. Stabilization processes are now offered by other firms such as the Environmental Technology Corporation, IU Conversion Systems, Inc., and the Dravo Corporation. The latter two firms are primarily oriented toward the stabilization of sulfur dioxide scrubber sludge.

The stabilization of waste materials by the addition of chemical agents is included in this report because, in particular instances, the process is a viable means for controlling potential pollutants. However, this process is not feasible for in situ landfill problems because the success of the system is dependent upon the intimate mixing of the chemical agents and the material to be stabilized; without this necessary mixing, the municipal refuse cannot be coated and encapsulated and, hence, the normal landfill processes of degradation and leaching will not be prevented. To ensure the mixing of the chemicals with the refuse would require excavating the entire landfill, which would provide little advantage over excavating and relocating the material to an environmentally sound site.

An alternative to the application of chemical fixation agents to the in situ landfill is the use of these agents to stabilize waste materials for use as a cover for a problem landfill. After proper processing, these waste materials can be spread, graded, and thereafter cemented into a stable, relatively impermeable cover (see Figure 16). It may be necessary to obtain a permit to use chemically stabilized waste materials as a landfill seal.

An ideal situation would be a problem landfill located near a source of chemically stabilized waste material. The material would be readily available and could be applied to the landfill as a cap. The landfill surface would first have to be regraded, as necessary to contours close to the desired final grade. The chemically stabilized material would then be applied at an

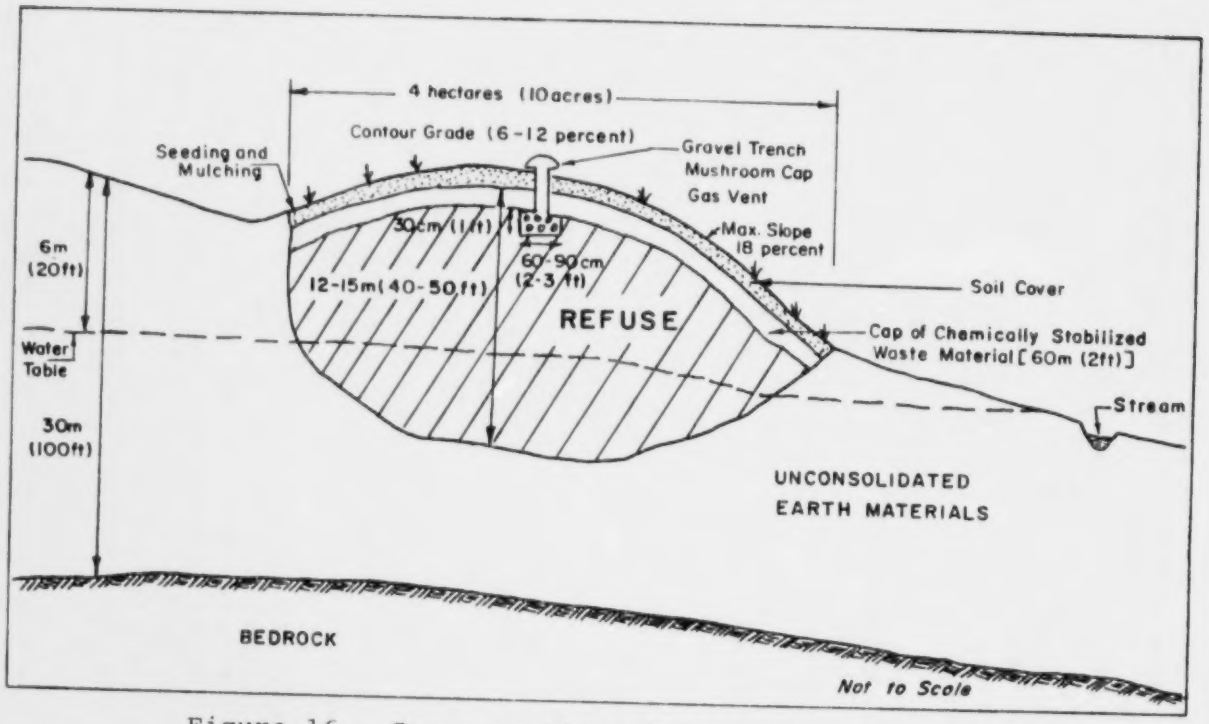


Figure 16. Cross section of landfill sealed with stabilized waste material.

approximate compacted thickness of 0.6 m (2 ft), with appropriate drainage swales to remove surface water.

As with any surface seal, provisions would have to be made for gas venting. A gravel trench the length of the site with mushroom cap vents at periodic intervals is one recommended method (see Figure 16). It is recommended that the landfill be covered with soil and revegetated (see Revegetation section).

Costs

The amount of stabilized waste material required for a 0.6-m (2-ft) cover on the 4-hectare (10-acre) landfill will total 25,460 m^3 (33,300 yd^3). Since it is a waste material, it is assumed that it will be available at no cost. The project costs, then, will include: (1) site preparation, (2) handling of cover material, and (3) spreading and grading. It is estimated that the cost of site preparation, spreading, and grading will range between $33,300 and $56,600.

The additional and major cost of material transportation is dependent upon the distance and time of travel between the source of the material and the landfill. This cost will be a function of the type and condition of the roads and the traffic flow. This additional cost will vary considerably, but for rough estimating purposes, at a 16-km (10-mile) distance a transportation cost of $65,000 is calculated, and at a 48-km (30-mile) distance a cost of $135,000 is estimated.

Unit costs used in these calculations include unit cost items 8, 9, and 10 (see Appendix).

Evaluation

Advantages--

1. The use of a waste material to cover and seal a landfill solves two environmental problems: (1) it neutralizes a leaching landfill and (2) it provides an environmentally acceptable means of disposing of a waste material.

2. Compared with common cover materials, most chemically fixed solids when properly compacted are quite impermeable.

3. The method is cost effective when the distance between the source of the waste material and the landfill is not great.

4. Construction methods are simple.

Disadvantages--

1. Waste materials used for sealing must be tested to ensure

that they will not release toxic levels of sulfates, chlorides, and other pollutants.

2. Covering and sealing only prevents surface water infiltration and will not correct any landfill problems due to groundwater movement.

3. Normal landfill settling will tend to break the cover and seal and, thus, the site will require long-term maintenance.

Recommendations

Chemical fixation agents are useful in stabilizing waste materials used to cover and seal a landfill. This method can be used effectively in conjunction with other neutralization methods.

The application of fixation agents to stabilize in situ landfills however is not feasible because the intimate mixing of the agents with the waste cannot be accomplished without excavation.

References

For further discussion, see references 69 through 77.

CHEMICAL INJECTION

Description

This process entails injecting reactive chemicals into a landfill for the purpose of destroying or insolubilizing a pollutant. Although this procedure merits exploration, no report is available to date of its successful application.

Four factors restrict in situ chemical neutralization to special circumstances. First, the injection of chemicals into a common municipal landfill would only be temporarily effective. Within a relatively short period of time the chemical action of the neutralizing agent would be spent, and normal landfill processes would be generating new and contaminating leachate. Therefore, in situ chemical neutralization is most applicable to industrial waste contamination, and the remainder of this section considers only that circumstance.

The second qualifying factor is that this process is waste-specific. For example, free fluorides can be insolubilized by the application of solutions containing the calcium ion; many heavy metals can be insolubilized by the application of alkalis and/or sulfides; free cyanide can be destroyed by the application of a strong oxidizing agent; and hexavalent chromium can be insolubilized by the application of a strong reducing agent. Each industrial waste is a special case; it must also be recog-

nized that many pollutants are not subject to chemical control, whether landfilled or not.

A third limitation to the application of chemical injection is that the source of the contamination within the landfill as well as the plume of contamination and the concentration gradients within the plume must be well defined. This mandates an in-depth preliminary investigation.

Yet a fourth factor to consider is whether the objectionable material is entirely dissolved in the landfill leachate or is present in the landfill as both a solution and a dissolving solid. If the substances are completely dissolved, then the application of chemicals to these substances may terminate the pollution. However, if the material is also present in a solid form and its solubility cannot be decreased by the application of chemicals, then there is little probability that the destruction of the material through chemical addition can be 100 percent complete. It is more likely that after the chemical application, the normal landfill leachate will resolubilize the objectionable material and generate additional pollution. On the other hand, if the solubility of the material can be affected by changing the local chemistry, then the situation could be favorable for chemical injection.

Costs

For cost-estimating purposes we shall assume a hypothetical case as follows:

The hypothetical 4-hectare (10-acre) landfill received a single load of cyanide salts in fiber drums. Initial probing and limited excavation confirms that the drums have been destroyed and the cyanide material has dissolved. An exploratory drilling and sampling program indicates a pollution plume as shown on Figure 17 and detailed in Table 3.

The corrective action selected in this case involves:

a. installing 45 well points on 15-m (50-ft) centers over the affected portion of the landfill;

b. pumping sodium hypochlorite solution into the wells (4 at a time); and

c. conveying water from a developed well (or available stream) to flood the landfill with the cyanide-neutralizing chemical.

The corrective action is depicted in Figure 18. The costs will be as follows (based on unit cost items 31, 32, 33, and 38 given in the Appendix):

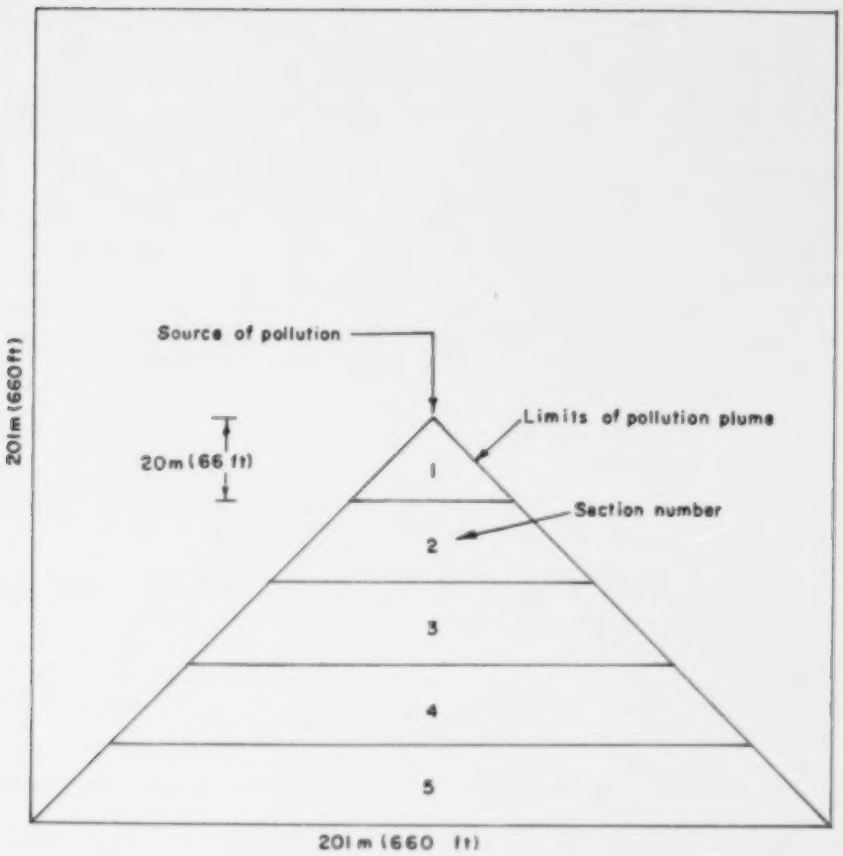


Figure 17. Pollution plume created by cyanide salts located in the middle of hypothetical landfill.

TABLE 3. REQUIREMENTS FOR CHEMICAL TREATMENT OF CYANIDE POLLUTION AT HYPOTHETICAL LANDFILL*

Section No.	Volume [m^3 (ft^3)]	Ave. Cyanide Conc. in Sect. (mg/liter)	Total Cyanide in Sect. [kg(lb)]	Sodium Hypochlorite Required Neutralization [liters(gal)]
1	5,490 (196,020)	200.0	320 (705)	21,773 (5,753)
2	16,470 (588,060)	50.0	240 (528)	16,305 (4,308)
3	27,440 (980,100)	13.0	104 (230)	7,086 (1,872)
4	38,420 (1,372,140)	3.1	35 (77)	2,363 (624)
5	49,400 (1,764,180)	0.78	12 (26)	789 (209)
	137,220 (4,900,500)		711 (1,566)	48,316 (12,766)

*Calculations based on landfill at density of 640 kg/m^3 (40 lb/ft^3) and 45 percent moisture (cyanide in solution in the moisture); available chlorine of 0.15 kg/liter (1.25 lb/gal) of sodium hypochlorite; chemical application rate of 68.09 liters/kg (8.16 gal/lb) cyanide (150 percent of theoretical).

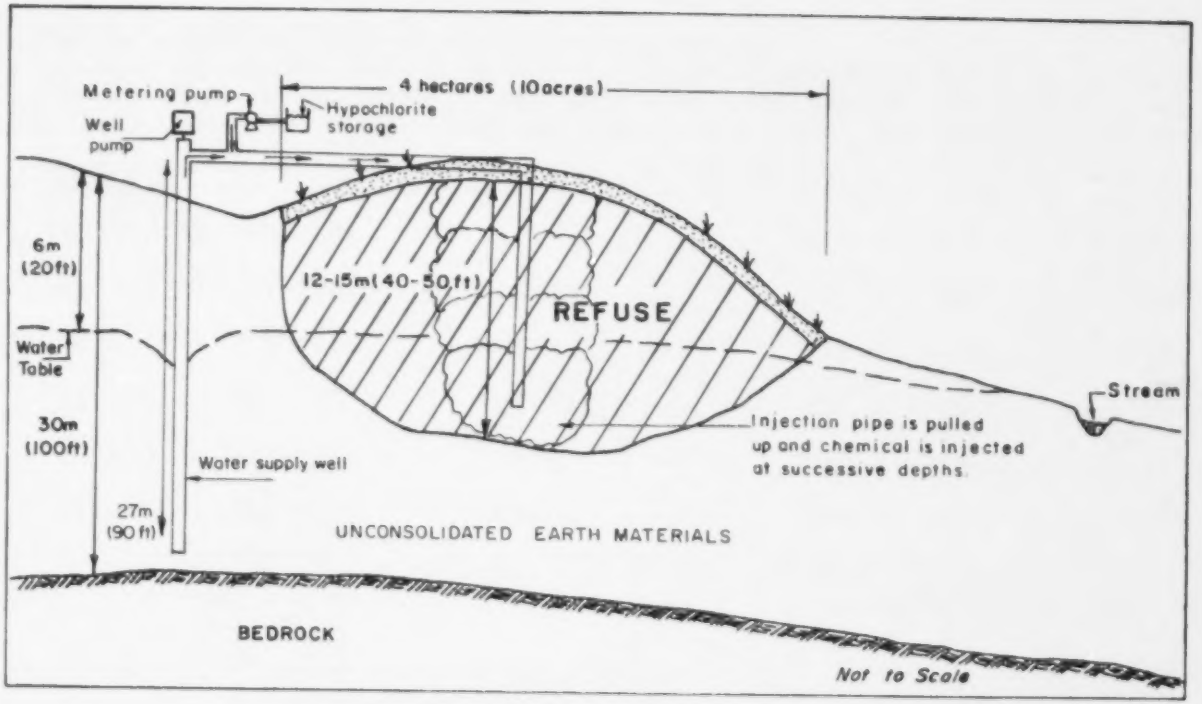


Figure 18. Cross section of landfill treated by chemical injection.

Exploratory probing, excavation, and drilling	$15,000
Development of water supply well, 27 m (90 ft); pump and piping	5,000
Installation of 45 well points	10,100
Cost of chemical feed pump	2,200
Cost of chemical	5,400
Labor for chemical injection, raising of well points to flood successive elevations (assumed 4 wells handled simultaneously), and general labor (1,600 hours)	48,000
Power (assumed electrical supply available	500
	$86,300

Evaluation

Advantages--

1. When the chemistry and circumstances are such that a hazardous material is amenable to chemical control, chemical injection may be a cost-effective method to correct a problem due to leaching.

2. The method could potentially control a hazardous situation in which no other alternative is feasible.

Disadvantages--

1. The fact that the source of the problem is buried deeply in the ground introduces many uncertainties such as the dimensions of the affected landfill volume, the concentration gradients in the system, whether any causative material is retained in drums only to continue to propagate the problem, etc.

2. Some displacement of the pollutant, perhaps to environs outside of the landfill, will occur due to the injection of the added volume of the chemical solution.

3. It would be difficult to measure the degree of effectiveness of this method.

Recommendations

Chemical injection is limited in application for landfill neutralization. However, when a known industrial pollutant is entirely dissolved in a landfill and its location or the location of its origin is well defined, this method could be effective in controlling pollution.

References

For further discussion, see reference 78.

SECTION 6

EXCAVATION AND REBURIAL

Description

The excavation and reburial of a landfill involves digging up the existing material, loading and transporting the waste to another site, and reburying it in accordance with accepted procedures. Before implementation of this technique, it must be established that the new site has better attenuation and pollution-controlling characteristics than the old site. A well-engineered existing landfill could be used to receive the waste or, for a particularly serious pollution problem, a new site could be designed.

It is recommended that a new reburial site be:

- located in slowly permeable materials or artificially lined to provide for leachate attenuation or collection and treatment;
- located at least as far above the water table as the depth of landfill, i.e., allowing 0.3 m (1 ft) of unsaturated low-permeability material for each 0.3 m (1 ft) of refuse deposited;
- located away from all public water supplies whether provided by surface or groundwater;
- engineered to provide for diversion of surface water, to promote surface drainage, and to include a low-permeability cover for sealing as described in the Surface Sealing section.

The composition of the wastes buried at the unsuitable site must be determined before equipment and procedures can be selected for excavating the waste. An investigation should be conducted by reviewing old records, digging test pits, and/or power augering. If it is determined that the landfill contains only municipal refuse, bulldozers, front-end loaders, and wheel-scrapers can be used for the excavation. For landfills that bury mixed solid wastes, additional equipment such as cranes fixed with large-materials-handling clamshell buckets, power shovels,

pull shovels, and crawler-type front-end loaders will be required. Dump trucks and rock-bodied vehicles can be used for transport.

Typical mixed wastes might include highway guard fence cable, railroad ties, bales of rags, large pieces of broken concrete, bed springs, rugs, drums of used oil and tar, auto bodies, large household appliances, asphalt pavement, paper, cardboard, garbage, tin cans, wire, tires, etc.

Excavation and reburial projects are often plagued by problems such as birds, rodents, flies, mosquitos, odors, blowing litter, wastes leaking during transport, and unanticipated types or depths of refuse. In one case recently, 9 m (30 ft) of refuse were to be excavated and removed; however, when this depth was reached, an additional 6 m (20 ft) of uncharted waste, limekilns, and buildings were discovered and had to be excavated.

Costs

The following costs are developed assuming the removal of the 4-hectare (10-acre) landfill, with depths of refuse between 12 and 15 m (40 and 50 ft), and transportation to a landfill 32 km (20 miles) distant. The assumption is also made that the receiving landfill is a permitted site and that no special preparation will be required. This example assumes dumping will be free of charge. Daily and final cover will be the responsibility of the receiving landfill.

Based on these assumptions, the cost to excavate, transport, and rebury the existing landfill [428,000 m^3 (560,000 yd^3)] will range between $3,495,000 and $5,645,000 for the hypothetical case.

The unit costs used in these calculations include items 7, 8, and 9 (see Appendix).

Evaluation

Advantages--

1. The source of contaminants is removed.

2. The wastes can be reburied in a controlled sanitary landfill, and the new site can be engineered to prevent environmental degradation.

3. The final land configuration of the original site can be designed to serve a useful purpose (e.g., a body of water could be created in the excavated landfill for recreation).

4. For excavated landfills over 10 years old, the fresh refuse would be on the bottom of the reburial site where it can

age, and the decomposed refuse would be on the top; therefore odor and vector problems would be minimized at the new site, and in some cases the decomposed refuse could be used as cover material.

Disadvantages--

1. Acceptable burial sites may be located long distances from the original site, in which case transportation could be costly. The condition of the haul roads, means of preventing leaky loads, and the accessibility of both sites are also important.

2. There may be political, social, and economic restraints to finding an acceptable reburial site. Restraints by governmental agencies are also a major consideration.

3. Excavation itself is difficult and often complicated by unwieldy materials and bulky or weighty demolition wastes.

4. There is a possibility of encountering hazardous wastes not documented (e.g., containerized volatile substances, pesticides, industrial process wastes, and pathogenic wastes).

5. If the landfill extends below groundwater, wet excavation will be involved and provisions must be made for disposition of the contaminated groundwater.

6. Nuisances and vectors must be controlled during excavation.

7. Reclamation of the excavated site will be necessary.

The excavation and reburial process can be a viable method of removing a polluting landfill if proper precautions are taken to control nuisances and vectors. Where the excavated waste must be hauled great distances [in excess of 48 km (30 miles)], transportation costs will be significant. Another cost factor which could be important is the preparation of the new landfill to receive the excavated wastes. Land acquisition for a new landfill in the vicinity may be difficult in terms of political and/or social opposition and monetary obstacles.

Recommendations

Excavation and reburial should be considered as a last resort since it is an extremely expensive and difficult procedure. There are, however, cases in which either the hazard of contamination is so severe or the water resources to be protected are so valuable that this method would be recommended.

REFERENCES

For further discussion, see references 78 through 82.

SECTION 7

SUMMARY

To minimize pollution from a solid waste disposal site, leachate generation and movement must be limited or controlled. Leachate production can be controlled by minimizing the amount of water entering the landfill. Reducing the amount of water in contact with the fill reduces the quantity of leachate generated. However, if the quantity of water is not sufficiently minimized, the pollutional load may not be reduced at all and, indeed, may be increased due to higher contaminant concentrations. Therefore, if water inflow reduction is to be used in landfill neutralization, the reduction must be significant.

It is generally not possible to reduce or eliminate the amount of moisture present in municipal refuse when collected. However, both vertical and horizontal percolation into the fill can be controlled by a number of techniques designed to either increase or decrease flow. The techniques considered herein have been grouped in five categories: surface water control, groundwater control, plume management, chemical immobilization, and excavation and reburial. It may be necessary to apply more than one method from more than one category to effect significant results. For ease of comparison, the major characteristics and estimated costs of these measures are summarized in Table 4.

SURFACE WATER CONTROL

Surface water infiltration can often be reduced during normal landfill closure if careful design and construction practices are followed. There are four ways to minimize water infiltration. The first is to increase runoff from the landfill surface by regrading to provide for moderate sheet flow from the surface. The second is to reduce the amount of runoff flowing onto the landfill surface by constructing diversion ditches and terraces. The third is to decrease infiltration into the landfill by applying a low permeability cover or seal to retard the vertical movement of water below the cover material. The fourth is to increase interception and transpiration of precipitation by planting vegetation on the landfill.

To increase runoff from the landfill by regrading, the surface should be sloped such that the water has the shortest

TABLE 4. SUMMARY OF ESTIMATED COSTS AND CHARACTERISTICS OF REMEDIAL METHODS

Method	Average Estimated Costs* ($ in Thousands)	Characteristics/Remarks
		Surface Water Control
Contour Grading	184	Increases runoff, reduces infiltration.
Surface Water Diversion	20	Diverts surface water from fill.
Surface Sealing		
Clay [15-46 cm (6-18 in.)]	234	If locally available, native clay is economical means of retarding infiltration.
Bituminous Concrete [4-13 cm (1.5-5 in.)]	315	Rapid coverage; can eliminate infiltration.
Fly Ash [30-60 cm (12-24 in.)]	235	Material may leach metals; may be available free.
PVC (30 mil)	482	Very impermeable; expensive seal; careful subgrade preparation is necessary.
Drainage Field (if required)	65	Carries infiltrated water off seal; increases effectiveness of seal.
Revegetation on Slopes <12 percent	10	Stabilizes cover material; seasonally increases transpiration; provides aesthetic benefit.
on Slopes >12 percent	19	
		Groundwater Control
Bentonite Slurry Trench	670	Simple construction methods; retards groundwater flow.
Grout Curtain	1,400	Very effective in permeable soils.
Sheet Piling	800	Widely used for shoring.
Bottom Sealing	4,000	Leachate collection may be needed; acts as a liner; difficult drilling through refuse.
		Plume Management**
Drains	23	Effective in lowering water table a few meters in unconsolidated materials; can be used to collect shallow leachate.
Well Point Dewatering	185	Suction lift limits depth to 7-9 m (20-30 ft); inexpensive installation; uses only one pump; can be used to collect shallow leachate.
Deep Well Dewatering	183	Used in lowering deep water tables; one pump needed per well; high maintenance costs.
Injection/Extraction Barrier	199	Creates a hydraulic barrier to stop leachate movement; operation and maintenance costs are high.
Spray Irrigation	336	Spreads leachate over the landfill for recycling; potential odor problem.
At-grade Irrigation	32	Gated pipe with ridge and furrow irrigation; potential odor problem; recycles leachate.
Subgrade Irrigation	28	Large-scale drainage field; recycles leachate.
		Chemical Immobilization
Chemical Fixation of Cover	145	Uses chemically fixed sludge to provide a top seal; provides means of disposal for sludge; helps stabilize landfill.
Chemical Injection	86	Immobilizes a single pollutant; in most cases not feasible.
		Excavation and Reburial
Excavation and Reburial	4,570	Very expensive; difficult construction.

*Costs for hypothetical 4-hectare (10-acre) landfill (see Figure 1). High and low estimates were averaged to determine these costs.
**Costs include present worth of 20 years, operation, maintenance, and, where applicable, power for 4-hectare (10-acre) landfill.

possible flow path from any point on the site. Thus a mound in the central portion sloping equally on all sides is an ideal regrading plan. Depending on the type of soil on the site, slopes of 6 to 12 percent are generally recommended. The cost of this regrading will depend upon the current grade of the landfill and the availability of local cover material. If major changes in grade are necessary, costs will escalate rapidly.

Diversion ditches are generally most useful in areas where the landfill is at the middle or the bottom of a slope and surface water collects upslope from the landfill and flows onto it. Standard construction techniques developed for handling storm runoff in highway and subdivision construction can be used to redirect surface water around a landfill. These techniques are generally not excessive in cost if the equipment used for regrading and covering operations is already available at the landfill.

If the material available for covering the site is highly permeable and if the landfill is in an area of high rainfall, surface sealing may be effective. A number of materials potentially suitable for sealing, in order of generally increasing costs, are local clay (where available), bentonite, bituminous concrete, asphalt, and plastic (PVC) membranes. These materials can markedly reduce infiltration into the landfill. In cases where low permeability cover material is to be placed over the seal, it may be necessary to construct a drain on top of the seal to carry away water intercepted by it. A properly constructed seal can reduce infiltration essentially 100 percent.

Revegetation of the completed landfill surface is recommended in favorable climates to stabilize the final cover material, aesthetically upgrade the area, and seasonally increase evapotranspiration of precipitation. Procedures for vegetating the landfill surface are very similar to those used in stabilizing highway grades and other areas of recent construction. The surface can be hydroseeded with a suitable grass mixture and mulched with a straw mulch. Steep slopes can be treated with legumes or vetch to hasten stabilization. Overland runoff over unvegetated soils rapidly erodes most cover materials and destroys the final grade. Therefore, vegetation is strongly recommended in most areas.

GROUNDWATER CONTROL

Subsurface infiltration barriers, or passive groundwater control measures, are designed to either prevent groundwater from flowing through the landfill and generating leachate or control the movement of leachate away from the landfill. Barriers are constructed of low permeability materials to divert and impede groundwater flow in the vicinity of the landfill. The engineering technology associated with groundwater barriers has been

developed for use in constructing cutoff walls around and under dams and excavation control structures in areas of shallow groundwater, e.g., at the sea coast. Barriers that can be used at landfills include slurry trenches, grout curtains, sheet pilings, and landfill bottom sealing.

Slurry trenches are constructed by excavating a trench through a bentonite slurry using draglines. The bentonite slurry is continuously pumped into the excavation and serves to stabilize the nearly vertical wall of the trench and ultimately to seal the area. The excavation is often carried to bedrock or other low permeability layer but can be terminated at shallower depths. Although costly, slurry trenches are generally the least expensive form of passive groundwater barrier.

Grout curtains are emplaced by forcing a thin cement grout through tubes which are driven deep into the ground on 2- to 3-foot centers and withdrawn slowly. Two or more rows of grout are usually needed to provide a seal. Like a slurry trench, the grout is generally emplaced down to an impermeable layer. Grout curtains are quite expensive when constructed to the dimensions necessary to cut off groundwater flow in the vicinity of a reasonably sized landfill.

Sheet piling has been extensively used in near-shore and offshore construction to stabilize areas for excavation. It is driven into the ground with a pile driver so that depending on the design the piles either butt or interlock. For sheet piling, as for all of the passive groundwater barriers, unconsolidated material must be present around the landfill with no large stones or boulders as these will deflect or prevent the piling from being effectively driven. Sheet piling is generally very expensive when used in the quantities necessary at landfills.

Bottom sealing of a landfill is like emplacing a grout curtain in a bowl shape under the landfill. Grout tubes are driven through the landfill, which can entail considerable expense because of bulky or resistant refuse. A bottom-grouted landfill would be similar to an engineered landfill with a liner except that the seal would be emplaced after filling. Generally speaking, unless the sources of leachate generation were removed, leachate collection would be necessary with a bottom-grouted landfill.

PLUME MANAGEMENT

The purpose of plume management or active groundwater management is to manipulate the water table in the area of the landfill to either prevent the formation of leachate or contain its spread. To do this, water must be extracted from or added to the groundwater system through drains, shallow well points, or deep wells. The capital costs of these systems are generally

much lower than those of passive barriers, but the operation and maintenance costs are considerably higher since in most cases a continuing supply of electrical power and ongoing maintenance of pumps and wells is required.

The technology of drains has been developed for use in agriculture, highway, and construction. Drains can be a low-cost means of lowering the water table a few meters provided the area in which the drain is to be emplaced can be readily excavated. Drains can be used to lower the water table upgradient of the fill, to collect leachate if it is following a shallow flow path, or to introduce leachate over the refuse on top of the fill. Drains are generally constructed using crushed stone and perforated pipe. Construction costs are comparatively low providing the depth of drain emplacement is not excessive. However, when highly mineralized waters are present, drains are more susceptible to clogging and maintenance costs may be significant.

Well points are widely used in construction to dewater shallow excavations. They are effective up to the limits of suction lift, i.e., 7 to 9 m (20 to 30 ft) below the ground. The main advantage of well points is that a large number of wells can be powered using a single suction pump. They are effective for dewatering shallow landfills and collecting shallow leachate. The installation cost for well points is moderate but maintenance can be relatively high since a good vacuum must be maintained on the entire system.

Deep wells can be used to dewater consolidated formations or areas where the water table is too deep for economical use of suction lifts or drains. Construction and operation of deep wells is a relatively simple but long-term operation, and maintenance costs can be high especially if the wells are used to collect leachate.

Any of these systems can be used to inject water into an aquifer to provide a groundwater barrier to the flow of leachate. This technology has been developed and applied in controlling the spread of sea water into potable aquifers and is potentially applicable to control leachate movement toward important well fields. However, the operation and maintenance costs are high and the leachate is only rerouted from its path, the quantity generated is not reduced.

The use of any of these systems for leachate collection will necessitate some means of leachate disposal. It is often feasible to recycle the leachate onto the landfill to hasten landfill stabilization. Leachate can be recycled by spray irrigation, at-grade irrigation, or subgrade irrigation (i.e., drains and tile fields). Spray irrigation involves the highest capital, energy, and maintenance costs, but also provides some leachate treatment and recycling. At-grade irrigation considerably reduces the

power requirements but shares with spray irrigation potential odor problems. Subgrade irrigation provides little direct leachate renovation but avoids the potential problem of having large quantities of leachate exposed at the ground surface. Generally speaking, landfills will stabilize more rapidly with leachate recycling. Potentially, a leachate collection system could be abandoned when the landfill has stabilized.

All of these groundwater management schemes involve a long-term commitment of manpower and funds to the maintenance and operation of the systems. Probably the least operation and maintenance costs would be required using drains and the most using a leachate collection and recycling system. However, there may be cases where any or all of these measures will be applicable and necessary for leachate control.

CHEMICAL IMMOBILIZATION

Chemical immobilization is a developing technology used to stabilize the waste and/or cover material through a chemical reaction. The method involves either the emplacement of a chemically stabilized low permeability cover or the injection of a chemical into the refuse and leachate plume to destroy a contaminant. The technology for chemical immobilization originated in chemical engineering and sludge stabilization work.

The first use of chemical immobilization is identical in intent to top sealing but uses a chemically stabilized waste product, i.e., sludge, to form a low permeability blanket on top of the landfill. In areas where this would be permitted, this method would have the beneficial effect of disposing of a waste product and at the same time aiding in the stabilization of the landfill. Most chemical immobilization processes are proprietary, but in general they involve either a cement base or chemical reaction base process. When a suitable waste material is available within reasonable distance of the landfill, this procedure can be cost-advantageous over other top sealing technology.

The other form of chemical immobilization is the injection of a chemical to destroy or tie up a specific pollutant. Generally speaking, any one chemical is effective only against one or two types of pollutants. This process is potentially very expensive but would be applicable in areas where a known hazardous material, such as cyanide, had been employed and was migrating with the groundwater. Chemical immobilization is a developing field and, at present, most methods of chemical immobilization would not be feasible for municipal refuse.

EXCAVATION AND REMOVAL

The purpose of excavation and removal is to move the

leachate-generating material to a better engineered or environmentally less sensitive area. Although conceptually very simple, excavation and reburial is expensive as well as practically and politically difficult. Basically, the process involves removing the entire contents of the landfill with common construction procedures and moving them, usually by truck, to another area where a better engineered and sited landfill is available. Problems arising in excavation and reburial include the technical problems of removing large quantities of bulky and partially decomposed wastes from the landfill, transporting partially saturated and saturated material over public roads without spillage or leakage, and cleaning up a leachate-filled pit after the waste material has been removed.

In addition, in most cases there are political constraints on the movement of such material through any populated areas, and there may be considerable local opposition to the importation of municipal refuse to an existing or new landfill. The process is in any case very costly, but in areas where a severe leachate problem has developed and a properly designed landfill is available nearby it may be applicable.

In summary, we believe that surface regrading and revegetation will be useful and necessary at practically all landfills and that surface sealing will be a useful adjunct to this where no natural low permeability cover is available. Groundwater manipulation is potentially very effective in areas where either much of the landfill is below the water table or the leachate is moving toward an important public water supply. Leachate collection and recycling may be a useful part of groundwater control. Chemical immobilization is a relatively new technology whose applicability will increase as more techniques are developed; however, the use of a stabilized sludge or other waste product for cover or sealing material appears to be feasible in areas where it would not be prohibited by local authorities and where the material is locally available. Excavation and reburial should be generally considered as a last resort which would be used only when all efforts to stabilize the refuse in place appear to be futile. Although it is potentially very effective it is also a difficult and expensive undertaking.

In the selection of remedial measures for use in minimizing pollution at any waste disposal site, professional feasibility assessment and design will be necessary.

REFERENCES

1. U.S. Department of Interior. Bureau of Reclamation. Earth Manual. First Ed., U.S. Government Printing Office, Washington, D.C., 1960. 751 pp.

2. U.S. Department of Agriculture. Soil Conservation Service. Soil Survey for Montgomery County. Pennsylvania, April 1967. 187 pp.

3. American Association of State Highway Officials. A Policy on Landscape Development for the National System of Interstate and Defense Highways. Washington, D.C., 1961. 38 pp.

4. Erosion and Sediment Control: Surface Mining in the Eastern U.S.--Planning. EPA -625/3-76-006, U.S. Environmental Protection Agency, Washington, D.C., Oct. 1976. 182 pp.

5. Erosion and Sediment Control: Surface Mining in the Eastern U.S.--Design. EPA -625/3-76-006, U.S. Environmental Protection Agency, Washington, D.C., Oct. 1976. 136 pp.

6. U.S. Department of Agriculture. Soil Conservation Service. Standards and Specifications for Soil Erosion and Sediment Control in Developing Areas. College Park, Maryland, July 1975.

7. Flower, F. B. and I. A. Leone. Damage to Vegetation by Landfill Gases. The Shade Tree, 50 (6.6):62-72.

8. Flower, F. B., et al. Vegetation Kills in Landfill Environs. EPA-600/9-77-024, U.S. Environmental Protection Agency, Cincinnati, Ohio, Sept. 1977.

9. Leone, I. A., et al. Damage to Woody Species by Anaerobic Landfill Gases. J. Arboriculture. 3(12):221-225.

10. Leone, I. A., et al. Damage to New Jersey Crops by Landfill Gases. Prepared for U.S. Environmental Protection Agency, Solid and Hazardous Waste Division, Grant #803 [illegible]-02, April 1977.

11. Rachel, J. Solid Wastes Disposal Impends on Landfill Technique. Solid Waste Management, June 1977, p. 50. (University of Wisconsin Ext., Landfill Course Lesson #3.)

12. Reindl, J. Managing Gas and Leachate Production on Landfills. Solid Waste Management, July 1977, p. 30. (University of Wisconsin Ext., Landfill Course Lesson #4.)

13. The Asphalt Institute. Asphalt for Water Control and Environmental Preservation. Information Series No. 164(15-164), Dec. 1973. 17 pp.

14. Marks, B. D., and T. A. Haliburton. Acceleration of Lime-Clay Reactions with Salt. J. Soil Mech. Found. Div., ASCE, Vol. 98, No. SM4, Proc. Paper 8827, April 1972. pp. 327-339.

15. Soil-Cement Construction Handbook. Portland Cement Association, Chicago, Illinois, 1956.

16. Pennsylvania Department of Transportation. General Specifications for Lime Subgrade Stabilization. St. Davids, Pennsylvania, 1974.

17. Interagency Engineering Committee. Soil Aggregate Gradations and Descriptions, New Jersey, undated.

18. Pennsylvania Department of Transportation. From 408: Specifications. Sections 332 and 333, Harrisburg, Pennsylvania, 197-.

19. What's New in Landfill Liners. The American City & County, Feb. 1977. p. 54-56.

20. Phillips Petroleum Company. Petromat Liners. Bartlesville, Oklahoma. 30 pp.

21. Haas, H. F., Jr., and R. M. White. Evaluation of Liner Materials Exposed to Leachate. EPA-600/2-76-255, U.S. Environmental Protection Agency, Cincinnati, Ohio, Sept. 1976. 54 pp.

22. Swope, G. Srvey of Revegetation on Sanitary Landfills. Unpublished M.S. Thesis, Pennsylvania State University, 1972.

23. Pennsylvania State University. Agronomy Guide, 1972-1978. State College, Pennsylvania, 1977. pp. 65-67.

24. Flowers, F. . Environmental Impact of Landfill Gas. University of Wisconsin Ext., Rutgers University, New Brunswick, New Jersey, 1976. 5 pp.

25. Blaney, H. F. Water and Our Crops. In: Water - The Yearbook of Agriculture. U.S. Department of Agriculture, Washington, D.C. 1955.

26. Blaney, H. F. Monthly Consumptive Use Requirements for Irrigated Crops. In: Proceedings ASCE - Irrigation and Drainage Division, Vol. 84, No. IRI, 1959.

27. Rosenberg, N. J., H. E. Hartand, and K. W. Brown. Evapotranspiration - Review of Research. MP 20, Agr. Exper. Sta., University of Nebraska, Lincoln, Nebraska, 1968.

28. Molz, F. J., S. R. VanFleet, and V. D. Browning. Transpiration Drying of Sanitary Landfills. Groundwater, 12(6):391-98, 1974.

29. Molz, F. J. Discussion of Transpiration Drying of Sanitary Landfills. Groundwater, 13(5):451, 1975.

30. Ham, R. K., and R. Kranauskas. Leachate Production from Milled and Unprocessed Refuse. University of Wisconsin Ext., 1975. 14 pp.

31. U.S. Department of Agriculture. Grass - The Yearbook of Agriculture. Washington, D.C., 1948. 892 pp.

32. Neumann, V. Possibilities of Recultivation of Refuse Dumps. Muell and Abfall, 3(1):5-18, Jan. 1971.

33. U.S. Department of Agriculture. Land - The Yearbook of Agriculture. Washington, D.C., 1958. 605 pp.

34. U.S. Department of Agriculture. Crops in Peace and War - The Yearbook of Agriculture. Washington, D.C., 1950-51. 942 pp.

35. Krynine, D. P., and W. R. Judd. Principles of Engineering Geology and Geotechnics. McGraw-Hill Book Co., New York, 1957. 730 pp.

36. Tschebotarioff, G. P. Soil Mechanics Foundations and Earth Structures. McGraw-Hill Book Co., New York, 1951. 655 pp.

37. Field and Office Manual. Engineering News-Record, New York, 1965. 128 pp.

38. Lanahan, T. There is a Place for Grouting in Underground Storage Caverns. Bull. Assoc. Engr. Geol., 10(2):137-66, 1973.

39. Kapp, M. S. Slurry-trench Construction for Basement Wall of World Trade Center. Civil Engineering, ASCE, April 1969. pp. 58-61.

40. American Colloid Company. Volclay Product Literature. Nos. 229-M, 230-G, 270-A, 280-A, Skokie, Illinois, 1972.

41. Applied Nucleonics Company, Inc. Technical Information Summary: Soil Grouting. Prepared for U.S. Environmental Protection Agency, Dec. 1976. 15 pp.

42. Gerwick, B. C., Jr. Slurry-trench Techniques for Diaphragm Walls in Deep Foundation Construction. Civil Engineering, ASCE, Dec. 1967. pp. 70-72.

43. Bentonite Slurry Stabilizes Trench, Keeps Groundwater Out. In: Field and Office Manual. Engineering News-Record, New York, 1965. pp. 70-73.

44. Calcium Bentonite Slurry Seals Canal. In: Field and Office Manual. Engineering News-Record, New York, 1965. p. 55.

45. Toronto's Cover-Then-Cut Subway. In: Field and Office Manual. Engineering News-Record, New York, 1965. p. 52.

46. American Colloid Company. Use of Bentonite as a Soil Sealant for Leachate Control in Sanitary Landfills. Data 280-E, Skokie, Illinois, Sept. 1975. 36 pp.

47. Raymond International, Inc. Siroc Grout Technical Manual. New York, 1967.

48. American Cyanamid Company. All About Cyanamid AM-9 Chemical Grout. Wayne, New Jersey, 1975. 95 pp.

49. Karol, R. H. Chemical Grouting Technology. J. Soil Mech. Found. Div., ASCE, Vol. 94, No. SM1, Proc. Paper 5748, Jan. 1968. pp. 175-204.

50. Halliburton Services. Grouting in Soils, Vol 2. Design and Operations Manual. PB-259044, U.S. Department of Commerce, NTIS, Springfield, Virginia, June 1976.

51. Revised Bibliography on Chemical Grouting. Third Progress Report of the Committee on Grouting, W. F. Seaman, Chmn. J. Soil Mech. Found. Div., ASCE, Vol. 92, No. SM6, Proc. Paper 4869, Nov. 1966. pp. 39-66.

52. U.S. Steel. U.S. Steel Sheet Piling: Design Extracts from Former Catalogs. ADV.-19605-52, Reprinted from Carnegie Steel Sheet Piling, Pittsburgh, Pennsylvania.

53. Bethlehem Steel Co. Bethlehem Steel Sheet Piling: Manufacturer's Catalogs. BPSCD859, Folders 2790, 2510, May 1971.

54. Bethlehem Steel Co. Steel Sheet Piling. Catalog 2620, Bethlehem, Pennsylvania, Oct. 1970.

55. U.S. Steel. Hot Rolled Steel Shapes and Plates, July 1963.

56. Bethlehem Steel Co. Bethlehem Structural Shapes. Catalog S-58-A.

57. Stubbs, F. W., Jr., Ed. Handbook of Heavy Construction. McGraw-Hill Book Co., New York, 1959.

58. Armco Drainage & Metal Products, Inc. Handbook of Drainage and Construction Products. The Lakeside Press, Chicago, Illinois, 1958.

59. Todd, D. K. Ground Water Hydrology. John Wiley & Sons, Inc., New York, 1959.

60. Dominico, P. A. Concepts and Models in Ground Water Hydrology. McGraw-Hill Book Co., New York, 1972.

61. The Johnson Division, University of Pennsylvania. Ground Water and Wells. Universal Oil Products Co., St. Paul, Minnesota, 1966. pp. 286-94.

62. Harr, M. E. Groundwater and Seepage. McGraw-Hill Book Co., New York, 1962.

63. Amar, A. L. Theory of Ground Water Recharge for a Strip Basin. Groundwater, 13(3):282-93, 1975.

64. Gregg, D. O. Protective Pumping to Reduce Aquifer Pollution. Glynn County, Louisiana. Groundwater, 9(5), 1971.

65. Nobel, D. G. Well Points for Dewatering. Groundwater, 1(3): 21-36, 1963.

66. Pound, C. E., R. W. Crites, and D. A. Griffes. Costs of Wastewater Treatment by Land Application. EPA-430/9-75003, June 1975. 154 pp.

67. The Asphalt Institute. Drainage of Asphalt Pavement Structures. College Park, Maryland, Manual Series No. 15 (MS-15), May 1966.

68. Shahan, M. T. Injection/Extraction Well System - A Unique Seawater Intrusion Barrier. Groundwater, 15(1):32-51, 977.

69. IU Conversion Systems, Inc. Pos-O-Pac, Pos-O-Pac, and Pos-O-Seal Product Literature. Philadelphia, Pennsylvania.

70. Mullen, H., L. Ruggiano, and S. I. Taub. The Physical and Environmental Properties of Poz-O-Tec. Engineering Foundation Conference on Disposal of Flue Gas Desulphurization on Solids, Hueston Woods State Park, Ohio, Oct. 1976.

71. Taub, S. I. Treatment of Concentrated Wastewater to Produce Landfill Material. Presented at Int. Poll. Engr. Exp. Congr., Anaheim, California, Nov. 1976.

72. Mullen, H., and S. I. Taub. Tracing Leachate from Landfills - A Conceptual Approach. Presented at the National Conference on Disposal of Residues on Land, St. Louis, Missouri, Sept. 1976.

73. IU Conversion Systems, Inc. Poz-O-Tec Process for Economical and Environmentally Acceptable Stabilization of Scrubber Sludge and Ash. Philadelphia, Pennsylvania.

74. Freas, R. C. The Stabilization and Disposal of Scrubber Sludges - The Dravo Process. American Petroleum Institute Committee on Refinery Environmental Control, Salt Lake City, Utah, Sept. 1975.

75. Hoffman, D. C. Calcilox - An Alternative to Slurry Waste Disposal Sites. Draft Report, U.S. Environmental Protection Agency, 1977. p. 36.

76. Snyder, G. A., and D. C. Hoffman. Effective Disposal of Fine Coal Refuse Using Calcilox Stabilization. Dravo Lime Company, Pittsburgh, Pennsylvania.

77. Conner, J. R. Ultimate Disposal of Liquid Wastes by Chemical Fixation. Presented at the 29th Annual Purdue Industrial Waste Conference, West Lafayette, Louisiana, May 1974.

78. Farb, D. G. Remedial Approaches for Upgrading Hazardous Waste Disposal Sites. Draft Report, U.S. Environmental Protection Agency, 1977. p. 36.

79. Sanitary Landfill Design and Operation. SW-65ts, U.S. Environmental Protection Agency, Washington, D.C., 1972. 59 pp.

80. Kellogg, F. H. Construction Methods and Machinery. Prentice-Hall, Inc., New York, 1954.

81. Roy F. Weston, Inc. Leachate Control Strategies for Llangollen Landfill. Preliminary Feasibility Study, West Chester, Pennsylvania, May 1976. pp. 57-59.

82. Roy F. Weston, Inc. New Castle County, Delaware Department of Public Works, Llangollen Landfill Rehabilitation Project. Recommended Plan. West Chester, Pennsylvania. 7 pp.

UNIT COSTS
USED AS BASIS FOR
COST ESTIMATES*

Item No.	Item	Range in Dollars/Unit	
1.	Unclassified excavation**	1.50 - 3.50/yd^3	2.00 - 4.50/m^3
2.	Borrow excavation, earth**	2.00 - 4.00/yd^3	2.60 - 5.20/m^3
3.	Borrow excavation, rock**	10.00 - 18.00/yd^3	13.00 - 23.40/m^3
4.	Diversion ditch/channel excavation**	6.00 - 9.00/yd^3	7.80 - 11.70/m^3
5.	Trench excavation** 0-7.6 m (0-25 ft)	12.00 - 18.00/yd^3	15.60 - 23.40/m^3
6.	Trench excavation** 0-24 m (0-80 ft)	15.00 - 30.00/yd^3	19.50 - 39.00/m^3
7.	Classified excavation - solid waste**	4.00 - 7.00/yd^3	5.20 - 9.10/m^3
8.	Materials hauling first 32 km (20 miles)	0.16 - 0.22/ ton-mile	0.24 - 0.32/ tonne-km
9.	Materials hauling additional cost over 32 km (20 miles)	0.07 - 0.12/ ton-mile	0.10 - 0.18/ tonne-km

* These unit costs are based on rates established in the Philadelphia Metropolitan area as of June 1977.
**Complete in place.

-continued-

UNIT COSTS
USED AS BASIS FOR
COST ESTIMATES
(Continued)

Item No.	Item	Range in Dollars/Unit	
10.	Fly ash and/or sludge spreading, grading, and rolling	1.00 - 1.70/yd^3	1.30 - 2.20/m^3
11.	Native clay material**	2.50 - 4.50/yd^3	3.30 - 5.90/m^3
12.	Bentonite (FOB Philadelphia, PA)	65.00 - 80.00/ton	71.50 - 88.00/tonne
13.	Bentonite slurry** 1053 kg/m^3 (65 lb/ft^3)	0.60 - 0.80/ft^3	17.70 - 28.20/m^3
14.	Portland cement grout**	4.00 - 10.00/ft^3	141.20 - 353.10/m^3
15.	Structural concrete**	125.00 - 180.00/yd^3	162.50 - 234.00/m^3
16.	Plain cement concrete pavement** 15-cm (6-in.) depth	6.00 - 10.00/yd^2	7.10 - 11.90/m^2
17.	Reinforced cement concrete pavement** 15-cm (6-in.) depth	8.00 - 13.00/yd^2	9.50 - 15.50/m^2
18.	Bituminous concrete pavement** 4-cm (1.5-in.) depth on 15-cm (6-in.) base course	3.00 - 5.00/yd^2	3.60 - 6.00/m^2

-continued-

UNIT COSTS
USED AS BASIS FOR
COST ESTIMATES
(Continued)

Item No.	Item	Range in Dollars/Unit			
19.	Bituminous concrete pavement** 4-cm (1.5-in.) depth	1.50 -	2.50/yd^2	1.80 -	3.00/m^2
20.	Bituminous concrete pavement** 13-cm (5-in.) depth	3.50 -	4.50/yd^2	4.20 -	5.40/m^2
21.	Reinforcing steel**	0.40 -	0.60/lb	0.90 -	1.30/kg
22.	Steel sheet piling PMA-22** 18 m (60 ft)	6.00 -	9.00/ft^2	64.60 -	96.90/m^2
23.	Piles HP 10 x 42**	7.00 -	12.00/ft	23.00 -	39.40/m
24.	Exploratory boreholes** 5-cm (2-in.) diameter	3.00 -	10.00/ft	9.80 -	32.80/m
25.	30-mil PVC membrane	0.30 -	0.60/ft^2	3.25 -	6.50/m^2
26.	French drains** 30 x 30 cm (12 x 12 in.)	1.00 -	2.00/lin ft	3.30 -	6.60/m
27.	15-cm (6-in.) foundation U-drains** 0.6 - 2.5 m (2 - 8 ft)	3.00 -	5.00/lin ft	9.80 -	16.40/m

-continued-

UNIT COSTS
USED AS BASIS FOR
COST ESTIMATES
(Continued)

Item No.	Item	Range in Dollars/Unit			
28.	15-cm (6-in.) foundation U-drains** 2.5 - 5 m (8 - 16 ft)	4.00 -	9.00/lin ft	13.10 -	29.50/m
29.	Seeding and soil supplements**	0.10 -	0.15/yd^2	1.20 -	1.80/m^2
30.	Mulching, hay or straw**	0.05 -	0.10/yd^2	0.60 -	1.20/m^2
31.	Well point, installed**	10.00 - 15.00/unit			
32.	Suction header, installed**	2.00 -	4.00/ft	6.60 -	13.10/m
33.	Suction pump, installed**	2,000 - 3,000/unit			
34.	Deep well, 15-cm (6-in.) PVC, drilled and installed**	15.00/ft		49.20/m	
35.	Well screen, 30-m (10-ft) PVC	100.00/ea			
36.	1.5- to 2.7-kw (1- to 2-hp) submersible pump and wiring	800.00 - 1,000/ea			
37.	PVC connection piping	2.00 -	4.00/ft	6.60 -	13.10/m
38.	Chemical (sodium hypochlorite, 14 percent)	0.42/gal		0.11/liter	

UNIT COSTS
USED AS BASIS FOR
COST ESTIMATES
(Continued)

Item No.	Item	Range in Dollars/Unit
39.	Labor for maintenance	7.75/hour
40.	Contract maintenance - drains (cleaning)	1,080/year
41.	Contract maintenance - spray irrigation	500/year
42.	Contract maintenance - at-grade irrigation (ridge and furrow)	185/year
43.	Contract maintenance - deep wells	386/year
44.	Contract maintenance - well points	1,080/year
45.	Portland cement or lime (FOB at plant)	30.00 - 31.50/ton
46.	Shipping cement or lime (100 miles)	15.00 - 22.00/ton
47.	Application of cement or lime for 13-cm (5-in) seal	1.85 - 2.10/yd^2